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An Update to the System Safety Study of TCAS II

Advanced System Acquisition Service
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16. Abstract

This report is an update to the System Safety Study of the Traffic Alert and Collision Avoidance System TCAS II. Since the time of the original study, and its companion study for instrument weather conditions, new data and new concepts have become available. Recent measurements of the Mode C reported altitude in general aviation aircraft strongly indicate that the errors assumed in the previous studies were overly conservative. On the other hand, new data on the vertical separation of aircraft at their closest point of approach indicates that this factor may have been too optimistic. The Advisory Invalid feature of the collision avoidance logic, which would provide a warning against an intruder's sudden levelling-off maneuver, has been replaced with an explicit reversal or increase rate, as the case may require. These and other new concepts in the collision avoidance logic greatly reduce the computed susceptibility to a sudden intruder maneuver, given reasonable pilot reaction. Several features were also introduced into the modified logic to improve interaction with the ATC system. The effects of all of these changes are taken into account in this update.

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FOREWORD

The investigation that is the subject of this report was undertaken in support of a rulemaking action by the Federal Aviation Administration, planned to be completed in the Fall of 1988. The report is a comparative analysis of system safety aspects of the Traffic Alert and Collision Avoidance System (TCAS II) as it appears in the Limited Installation Program (LIP), compared with improvements that are planned to be included in the rulemaking action.

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INTRODUCTION

This report is an update to the System Safety Study of the Traffic Alert and Collision Avoidance System called TCAS II (Ref.1). Since the time of the original study, and its companion study for instrument weather conditions (IMC), new data and new concepts have become available; this report assesses their effects.

APPROACH

The approach taken for updating this study is based on the earlier work; the main emphasis is on the relative improvement of the safety of flight—the probability of a near midair collision, or NMAC—with TCAS, as contrasted to that without TCAS. This ratio is called the Risk Ratio. In performing the calculations, many of the basic conditions and assumptions made earlier are repeated here. On the other hand, several are changed for this study as follows:

- New information is available on the accuracy of reported altitude for general aviation aircraft without air data computers.

- A substantially larger set of data is now available on the normal vertical separation of aircraft when they are close to each other; this has implications on the effectiveness of TCAS.

- There is a feature in the collision avoidance logic that avoids posting an altitude crossing Resolution Advisory (RA) whenever the desired separation (the variable designated ALIM) is predicted to be achievable by a non-crossing maneuver.

- There is a feature in the collision avoidance logic that, for an essentially level TCAS, would avoid posting an altitude crossing RA unless the aircraft are already within the altitude separation usually imposed by ATC.

- There is a feature in the collision avoidance logic that calls for a reversal of the previously-advised RA if appropriate.

- There is a feature in the collision avoidance logic that calls for an enhancement of a previously-advised RA ("increase vertical rate") if appropriate.

ALTIMETRY

One of the principal features of the earlier work was evaluating the effect that altimetry error would have on the overall safety of TCAS in the air traffic control (ATC) system. These errors were estimated based on specifications, regulations, industrial practices, and a small amount of experimental data. So

that, while this information was the best that was available at that time, more real data was needed. Three steps were thereafter taken by the FAA: one is the measurement of errors in reported altitude for general aviation aircraft flying in the traffic pattern; another is an ongoing effort at measuring altimetry errors at high altitudes; and a third is an assessment of the prevalence of "stuck bit" errors in an aircraft's altitude encoder.

To determine the low-altitude altimetry errors, instrumentation was set up at five airports that handle a large fraction of general aviation aircraft in the Northeast portion of the country. Data on a total of 203 operations were recorded as aircraft approached to and departed from the airports.

The results of these field measurements showed that, while the tails of the distribution were somewhat higher than the Gaussian (Normal) distribution previously assumed, the standard deviation of the error was substantially less than previously assumed (67 ft instead of 118 ft), making the earlier calculations quite conservative.

In assessing the errors of altimetry at high altitudes (all aircraft above Flight Level 290), the FAA Technical Center has been comparing physical altitudes, measured by an instrumentation radar, with pressure altitude, measured by Mode C replies. Periodic readings of atmospheric pressure obtained by specially instrumented aircraft flying through the field enabled them to convert these readings to Altimetry System Error. While the conclusions are not yet finalized, some early results are available. The standard deviation for all aircraft above Flight Level 290 appears to be about 105 ft, with a distribution that is very close to being "double exponential." In Ref. 1, the value used for altimetry error for general aviation aircraft at an altitude of 30,000 ft was 192 ft, with a Gaussian distribution. While the measured distribution was higher tailed, its smaller standard deviation is a strong compensation in the other direction. As a result, the high-altitude values used in the earlier studies also turned out to be very conservative.

The effect that altimetry error has on the Risk Ratio depends on the altimetry error, on the particular strategy that is used for vertical resolution, and on the vertical distribution of aircraft at their closest point of approach (CPA.) For updating the calculations, the measured 67 ft standard deviation is used as the basis for altimetry error in basic systems, but the form of the distribution will be assumed to be double exponential, thereby retaining the conservatism formerly sought, yet accounting for much of the new information that is now available. The modified logic uses a vertical resolution strategy of avoiding crossing altitudes, if at least a separation of the threshold called ALIM is predicted to be achievable; otherwise, the predicted separation is maximized as before. Using these errors and the non-uniform distribution of altitude separation at CPA, the effects of these errors are computed by the numerical integration method used in the previous studies. The net result is that the increase in Risk Ratio caused by the non-uniformity of altitude distribution is just about offset by the better-than-assumed magnitude for altimetry errors.

The third item in the study of altimetry was to obtain a higher confidence for the prevalence of the "stuck bit" condition. That is a situation in which one of the 12 Mode C bits remains stuck on or off well beyond the time that it should have changed. The major impact for TCAS is that if one of the least significant bits, a "C" bit, is the offender, it might go undetected by the ATC system and yet cause an

..or large enough to induce an NMAC. This possibility had been evaluated in the System Safety Study using the sparse data available at that time. In connection with the effort to learn more about altimetry errors, MITRE reviewed more than 190 hours of radar data taken in 1981 from the Seattle Automated Radar Terminal System (ARTS III). As it turned out, this happened to provide the same results as were used in Ref. 1, but now there is a greatly improved level of confidence.

MANEUVERING INTRUDER

When the intruder aircraft is not TCAS-equipped, its pilot may inadvertently introduce a maneuver of his own that defeats an escape maneuver by the TCAS aircraft. This only applies if the intruder aircraft does not have TCAS; two TCAS aircraft will by design always have complimentary maneuvers posted. Whenever a situation exists in which an altitude crossing is predicted, a sudden intruder maneuver could possibly thwart an avoidance maneuver on the part of the TCAS aircraft. In the current logic, this eventuality is handled by notifying the pilot of those instances in which the posted RA is no longer correct (the "Advisory Invalid" indication).

Major objectives of the modifications to the logic are, first, to minimize the number of altitude crossing maneuvers, and, second, to replace the Advisory Invalid indication with the best information available at that time. The modified logic, on detecting that a crossing encounter has seriously degraded and that the usual ATC altitude separations are no longer being maintained, will post a reversal RA, telling the pilot to reverse his escape maneuver from the former RA to a new RA. (Of course, if the aircraft are at nearly the same altitude when the level-off occurs, no reversal will be given.)

Estimates have been made of the separation achievable when the modified logic calls for a reversal. The calculations assume a pilot delay of 2.5 seconds (compared with 5 seconds for the initial maneuver) and a vertical acceleration of 1/3 g to 1500 fpm (compared with 1/4 g to 1500 fpm for the initial maneuver). These values, used to calculate the probability of being able to avoid an NMAC with a reversal, represent an urgent, but not violent, pilot reaction. The result is a substantial improvement in the susceptibility to failures caused by a suddenly maneuvering intruder.

In the current logic, the Advisory Invalid indication is used to signal any situation in which the effectiveness of the RA becomes seriously degraded, not only the one situation of major concern, the level-off. So if the Advisory Invalid feature is to be removed, some other provision must be introduced to handle those instances in which the intruder may increase its rate so as to degrade the RA. Such a feature has been included; when a non-crossing RA degrades sufficiently, the TCAS aircraft will be told to increase its vertical rate beyond the nominal 1500 fpm, or beyond the current rate if it already is greater than 1500 fpm. With this feature, it then becomes feasible to entirely eliminate the Advisory Invalid indication for handling maneuvering intruders.

EFFECTS OF PROPOSED FAA RULEMAKING

A major factor in favor of TCAS is the fact that no special equipment is necessary for the other aircraft—only the conventional ATC transponder with a Mode C altitude encoder (a substantial, but lesser, safety benefit still exists even if the intruder only has a transponder and not an altitude encoder). A further benefit can be expected if all air carrier aircraft are TCAS equipped.

This latter benefit occurs simply because TCAS substantially reduces the probability of an NMAC for each aircraft on which it is carried. If all air carriers had TCAS, as is contemplated in a current Notice of Proposed Rule Making, or NPRM, the total annual NMACs for air carrier aircraft would be effectively reduced by the net Risk Ratio for each of these aircraft. The individual Risk Ratio for any particular TCAS-equipped aircraft, however, would only be affected in a minor way. This is because NMACs between air carrier aircraft constitute only 9 percent of the cases, and air carrier aircraft with their air data computers mostly have corrected altimetry. The real benefit would be to minimize any failures caused by maneuvering intruders; however, conflicts between aircarrier aircraft (TCAS equipped) are coordinated by design. Nevertheless, the highest level of protection against a conflict between two air carrier aircraft, though not measurable in terms of significant probabilities, would thereby be provided.

Another NPRM requires the carriage of Mode C transponders by all aircraft within 30 nmi of the principal airport of a Terminal Control Area (TCA) or a Terminal Radar Service Area (TRSA). To give some idea as to the effectiveness of such action in relation to TCAS, the location of recent NMACs was investigated. The FAA provided this information on the 53 critical NMACs, involving at least one air carrier, that occurred within CONUS in 1986. It was found that 34 (63 percent) were either within 30 nmi of the principal airport of a TCA or TRSA, or else they were above 12,500 ft, where they are already required to carry Mode C transponders.

Thus 63 percent of all NMACs would be covered by the Mode C rules. The remaining 37 percent are then treated in the same manner as for the previous studies. The result is that 97 percent of the dangerous intruders would be expected to be equipped with transponders, and 86 percent of the intruders would have Mode C—a substantial improvement over the current situation.

ATC INTERACTION

In addition to evaluating the quantitative safety implications, it is also important to understand any impact that TCAS may have on the normal interaction of the aircraft flying in the ATC system. Among other things, the earlier IMC study addressed the potential for TCAS to cause a "domino effect" in dense regions of traffic, as well as for any tendency to disrupt aircraft flying on a parallel approach to an airport.

It was found that, rather than destabilizing the system, TCAS would bring an inadvertently deviating aircraft back to its clearance with no tendency toward becoming unstable (producing a domino effect).

In fact, the multiaircraft TCAS logic tends to prevent movement from propagating to additional aircraft. That study also showed that, for the traffic samples as provided by the ATC radar data tapes, all of the aircraft that would have received RAs would have passed within the IFR separation standards.

Another major concern that had been addressed, the parallel approach question, also produced similar results. That is, an RA would have occurred only if the vertical separation was too small too early in the approach. Following the aircraft tracks from the radar data, one could observe that the aircraft did indeed correct their vertical profiles at about the same time that they would have received an RA.

Subsequent to that study, concern has been raised over the possibility for TCAS to disrupt other situations in which both aircraft are flying normally ("by the rules"). Two situations are of concern: an encounter between two TCAS aircraft, in which one is transitioning in altitude; and an encounter in which an unequipped, non-TCAS, aircraft that is transitioning in altitude unnecessarily forces a level TCAS aircraft to leave its own cleared altitude.

TCAS-TCAS ENCOUNTERS

It can be shown that, even for a projected crossing encounter against a level intruder, a TCAS aircraft that was climbing or descending would reverse itself naturally and avoid crossing the intruder's altitude in the great preponderance of cases, especially for the modified logic. In a meeting of the Secondary Surveillance Radar Improvement and Collision Avoidance System Panel (SICASP) of the International Civil Aviation Organization, it was brought out that this type of encounter could either naturally fit in with ATC practice or it could introduce some awkward maneuvering, depending on which of the two TCAS aircraft were to detect the conflict first. That is, if, in a crossing encounter, the TCAS aircraft having the vertical rate detects the conflict first, it would most likely generate an RA that called for reducing or reversing its current rate, leaving the level TCAS aircraft essentially undisturbed, which in all likelihood was the intention of ATC. On the other hand, if the level TCAS aircraft were the first to detect the conflict, it would be more likely to see the crossing encounter as one that would have to be resolved by crossing the intruder's altitude. Since both aircraft in this scenario are TCAS, there is no danger of an uncoordinated action, as there might be if this were not the case, but it is highly unlikely that the intention of ATC is to set up such an encounter. Thus, there is a chance that a late ATC solution might be contrary to the TCAS solution.

The suggestion was made in SICASP that some means be taken to force the level TCAS to defer to the one having a substantial rate. This concept is included in the modified logic, where, in a crossing encounter, a substantially level TCAS (less than 600 fpm) will defer to a TCAS that has a vertical rate (greater than 600 fpm) for an interval up to 3.5 seconds. If the TCAS with the vertical rate does not detect the encounter and start the coordination process by that time, the level TCAS aircraft will proceed on its own. These features in the modified logic enhance the compatibility of TCAS with the ATC system.

FORCED ALTITUDE DISPLACEMENTS

The other concern is the possibility that a transitioning non-TCAS intruder might introduce a degree of disorder into the normal flow of traffic by causing frequent, large deviations of a level TCAS aircraft from its altitude clearance. Of course, if there is a real conflict and the aircraft are within the ATC separation standards, TCAS would be expected to provide an alert; it is just when all aircraft are following the rules and are properly separated that the concern exists.

The answer depends on the intruder's altitude rate and the projected miss distance. If the rate is great enough, and the vertical miss distance is within ALIM, TCAS will post a corrective RA, which will last until the intruder levels off at his own clearance, or until the the TCAS aircraft moves to achieve ALIM + 75 ft separation. After such action, the RA will downgrade and the TCAS aircraft will level off, thereby displacing approximately another 100 ft before it returns to its original altitude.

Using the distribution of vertical rates observed in the Piedmont Phase I Program, the expected results are shown for the current logic in Figure 1: 97 percent of these encounters would cause the TCAS aircraft to displace less than 300 feet, 3 percent between 300 and 400 feet, and the frequency of any larger displacements is too small to be estimated. For the modified logic, in which the RA would not be posted until the intruder had come to within 900 ft, forced displacement of substantial amounts would occur only on rare occasions.

In summary, the great majority of such encounters requires little displacement by the level TCAS aircraft, even with the current logic, so long as both aircraft seek to adhere to their IFR clearances. Any substantial overshoot or drift from cleared altitude assignments, however, would result in the posting of an RA and the resulting maneuvering to obtain clearance.

CONCLUSIONS

Since the original TCAS II System Safety Study and its companion IMC study were completed, new data has become available and some new concepts have been introduced to enhance the collision avoidance logic. For instance, several measurement programs designed more clearly to describe the accuracy in reported altitude of the present Mode C system have been completed. Similarly, a substantial data base of radar-recorded data has become available to more clearly describe the maneuvers of aircraft and their proximity in the dense airspace near terminal areas. At the same time, flight experience, especially of an operational nature, has occurred. Significantly, the collision avoidance logic has been modified to bias against altitude-crossing maneuvers, and to call for either a reversal of the TCAS' vertical rate or an increase of it, if determined to be necessary. These latter considerably improve the ability of TCAS to cope with maneuvering intruders.

An overall representation comparing the impact of these effects is depicted in Figure 2. In this Figure, the probability of a critical Near Midair Collision occurring today, without TCAS is represented by the column on the left. The next column shows the Risk Ratio that was computed previously in Ref. 1.

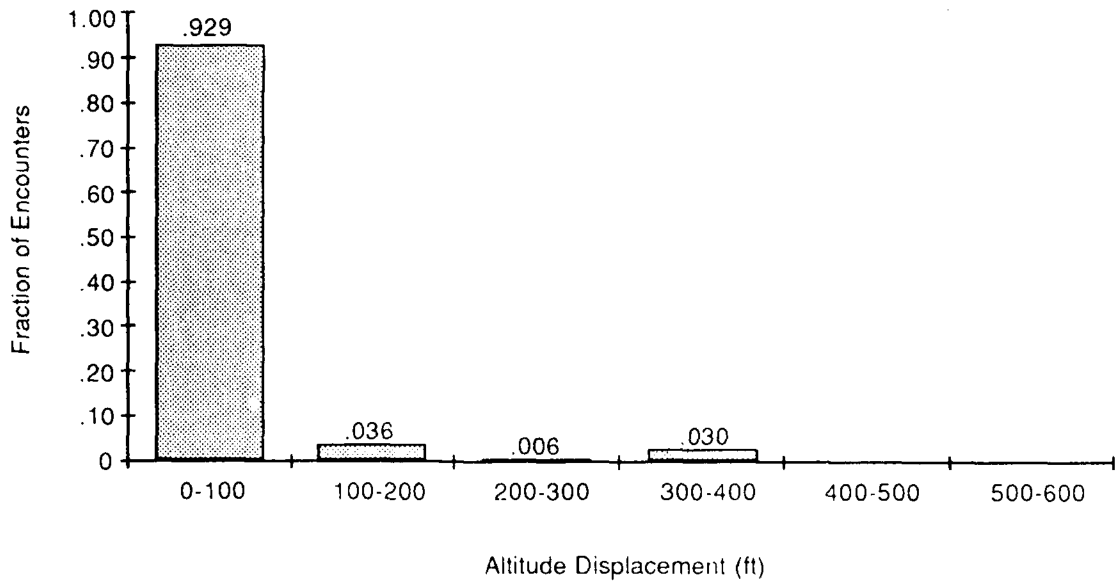

FIGURE 1
HISTOGRAM OF FORCED ALTITUDE DISPLACEMENTS

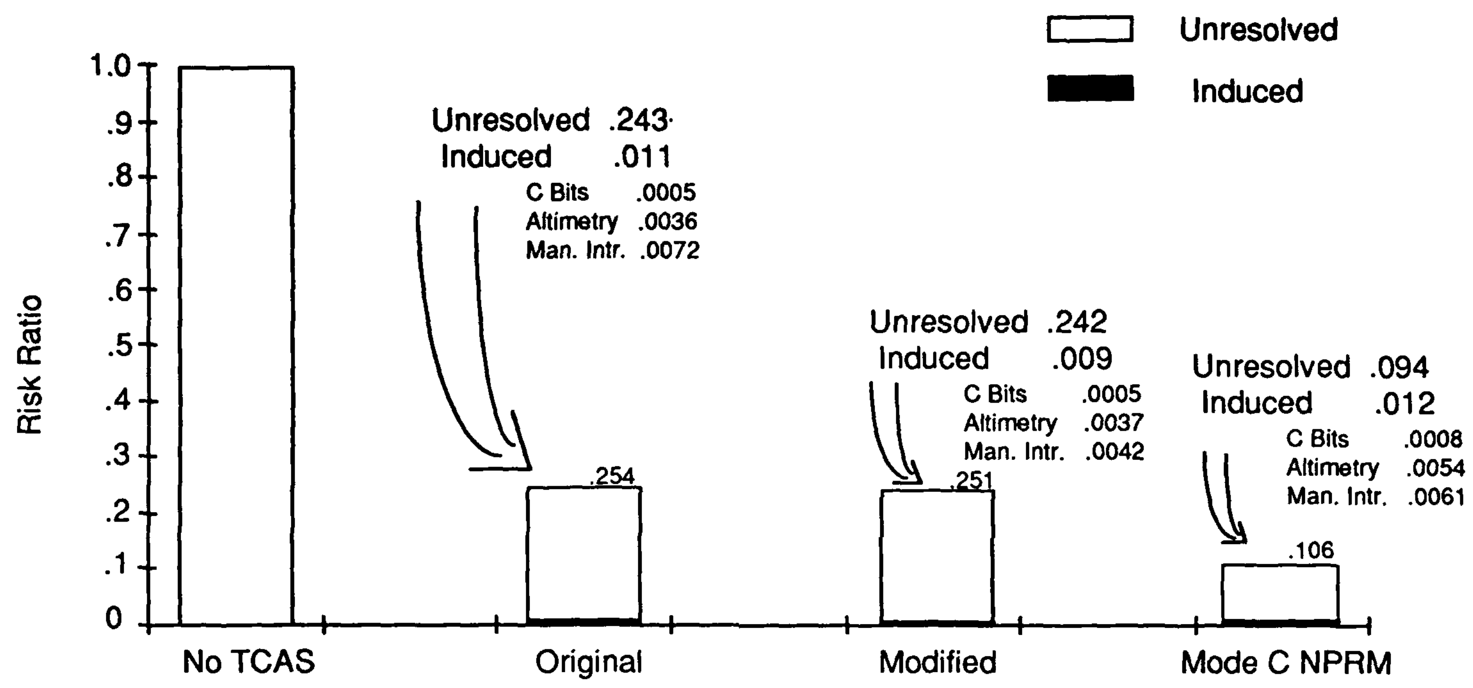

FIGURE 2
COMPARISON OF RESULTS

Susceptibility to maneuvering intruders was deemed to be the leading cause of induced failures, although not by a large factor. The total value for Risk Ratio is shown at the top of the column.

The third column represents the results of this study, which includes the updated information on altimetry, aircraft maneuvers, and modifications to the collision avoidance logic. The large unresolved component, being caused principally by aircraft flying without transponders and Mode C altitude encoders, remains virtually the same; the contribution of the maneuvering intruder to the induced component is somewhat reduced. The net result, however, is that the performance is very close to that which had been predicted formerly, the new factors tending to offset each other.

The fourth column represents the predicted effect of instituting the proposed rule that would require transponders and Mode C altitude reporting by all aircraft within 30 nmi of the principal airport of a Terminal Control Area or a Terminal Radar Service Area, a further improvement of about 2 to 1.

In summary, after about 5 years of additional investigation and development, the System Safety implications remain roughly the same. TCAS can be expected to resolve about 75-90 percent of the current critical near midair collisions (thereby presumably of actual midair collisions), while causing them on its own at a rate of about 1 percent (1 critical near midair collision in 10^7 flight hours or less than 1 actual midair collision in about 10^9 flight hours). For instrument weather conditions, both factors have been shown to improve somewhat, because the more organized structure and utilization of the airspace more than compensates for the assumed lack of visual acquisition.

SECTION 1

INTRODUCTION

In 1983, a System Safety study was undertaken for the Traffic Alert and Collision Avoidance System called TCAS II. Since that time, new data, modifications in the design of the collision avoidance logic, and new methods for operating TCAS modify somewhat the results that were obtained. In addition, some early experience has been gained with the system operating on the flight deck of a scheduled Piedmont Airlines aircraft, the Piedmont Phase II program, supplementing the earlier Piedmont Phase I program, where the system was on board the aircraft but not visible to the flight crew. Finally, an extensive in-service flight program, called the Limited Installation Program (LIP), is now under way. While that program includes minor upgrades to the collision avoidance logic, it is basically the same as for the earlier Piedmont Phase II effort. This report is an update to the System Safety Study (Ref. 1), in which the new concepts are assumed to apply.

TCAS II is an airborne collision avoidance system that presents both Traffic Advisories (TAs) and Resolution Advisories (RAs) against appropriate, transponder-equipped aircraft. Resolution maneuvers, when deemed necessary, are made in the vertical plane. This is addressed to the early introduction of collision avoidance technology into the airspace. A future system, TCAS III, is also undergoing development. That system would provide RAs in the horizontal plane as well as in the vertical plane, under appropriate conditions; it is not the subject of this report. This report also does not address TCAS I, a system intended to aid visual acquisition, which would provide only TAs, not RAs, for use in visual conditions.

Since this report is an update, familiarity with the preceding work will be assumed. This includes both the original System Safety Study itself and the subsequent study (Ref. 2) performed assuming instrument meteorological conditions (IMC). As in both previous studies, the emphasis of the quantitative calculations is for TCAS in an air carrier aircraft.[1]

A major objective of this effort is to eliminate the feature in the present collision avoidance logic that would recognize those conditions when the posted RA was no longer effective and post instead an indication that the RA was no longer valid ("Advisory Invalid"). Modifications to the logic, as given here and in Ref. 3, first, avoid these conditions as much as possible; and, second, present the best available information to the pilot, even under these conditions. Evaluation of these features is the central theme of this report.

This report reviews, in Section 2, the approach taken to quantify the level of system safety. It then summarizes, in Section 3, some new data that has been obtained on altimetry and reported altitude, as well as new data on the maneuvering of aircraft in dense airspace. This latter data, together with modifications to the collision avoidance logic, alter the results previously obtained for the effect of

[1]Throughout the earlier studies and in this one, the definition of "air carrier" aircraft includes commuter as well as air taxi aircraft; that is, aircraft in revenue service.

maneuvering intruders, and this is discussed in Section 4. As the overall results are naturally dependent on the situation regarding the deployment of equipment, both Mode C transponders and TCAS, Section 5 very briefly summarizes this situation. A review and update of some of the ways that TCAS and the air traffic control (ATC) system are anticipated to interact is discussed in Section 6. Finally, Section 7 presents the conclusions; supporting information is given in the appendixes and the references.

SECTION 2

APPROACH

The approach taken for updating this study is based on the earlier work; the main emphasis will be on the relative improvement for the safety of flight with TCAS as contrasted to that without TCAS (Risk Ratio). The assumptions remain the same as before except where some new information is introduced; the methods for obtaining the quantitative results are also based on the earlier work.

2.1 RISK RATIO

The concept of the Risk Ratio is used as it was previously. Risk Ratio is the ratio of Critical Near Midair Collisions (hereafter termed simply NMAC) when the aircraft is equipped with TCAS, relative to the NMACs without TCAS. Using the definition of a Critical NMAC from p. 1-5 of Ref. 1 (aircraft come within 100 ft vertically and 500 ft horizontally), it is relatively straightforward to calculate any factors that either improve (resolve) or degrade (induce) the likelihood of an NMAC. By focussing on the Risk Ratio one can sidestep the problem of having to estimate the probability of the aircraft being simultaneously close in the horizontal plane and in the vertical plane, since that occurs automatically by the very definition of an NMAC. It also avoids having to accurately determine the probability of an NMAC today, without TCAS; although, that figure is also estimated.[2]

2.2 BASIC CONDITIONS

In performing the calculations, many of the basic conditions and assumptions made earlier are repeated here. The major assumptions are listed below:

- As a start, the intruder environment, that is, the types of aircraft encountered, the altitudes and speeds at which they fly, and their equipage is assumed to be the same as previously determined, using both the equipage statistics derived in Ref. 1 and the Piedmont Phase I experience (this has recently been revalidated by results of the Piedmont Phase II experience)[3].

[2]The real objective, of course, is to avoid an actual midair collision (MAC). While there is, fortunately, sparse data to relate the MAC to the NMAC, it is usually considered to occur about 100 times less often.

[3]As will be discussed, an analysis of traffic made by the United Kingdom will be accounted for, as will a Notice of Proposed Rule Making for enhanced Mode C equipage.

- The risk of an air carrier aircraft encountering a critical NMAC without TCAS remains at 1 in 100,000 flight hours (probability = 10^{-5}), as was previously determined.[4]

- Accounting for the continuity of surveillance and for visibility conditions remains the same as determined formerly.

- The pilot will be assumed to nominally follow the recommended TCAS maneuvers, will not prematurely maneuver on TAs only, and will safely avoid a collision, regardless of TCAS, if visual acquisition is obtained in sufficient time.

On the other hand, there are several basic conditions that are changed for this study as follows:

- New information is available on the accuracy of reported altitude for general aviation aircraft without air data computers.

- A substantially larger set of data is now available on the normal vertical separation of aircraft when they are close to each other; this has implications on the effectiveness of TCAS.

- There is a feature in the collision avoidance logic that avoids posting an altitude crossing RA whenever the desired separation (the variable designated ALIM) is predicted to be achievable by a non-crossing maneuver.

- There is a feature in the collision avoidance logic that calls for a reversal of the previously-advised RA if appropriate.

- There is a feature in the collision avoidance logic that calls for an increased rate in the direction of the previously-advised RA if appropriate.

The effects of these new factors will be explored.

2.3 METHODOLOGY

The method that will be used here is to note the changes that have occurred from the System Safety Study. It was shown that there were two major problems that needed to be addressed: altimetry and the maneuvering intruder. All other possible causes for a failure that might lead to a TCAS-induced NMAC were essentially negligible compared to these two. The altimetry issue will be addressed by considering the new data that is now available, as detailed in Section 3, and by evaluating the effects of

[4]Early results of the Piedmont Phase II program indicate that the rate of RAs, and therefore of NMACs, may have about doubled since the 1983 Phase I program. This is also corroborated by the critical NMAC statistics collected by the FAA. However, since the figure of 10^{-5} was conservative in the first place, its use will be retained here.

some new criteria for vertical escape maneuvers. The maneuvering intruder issue will be addressed by evaluating the effects of modifications to the collision avoidance logic that have been designed to cope more effectively with this condition, as detailed in Section 4.

One of the key assumptions used in both these aspects of the former work was that the vertical separation at the closest point of approach was uniformly distributed; this assumption was derived from observations of experimental data. More recently the United Kingdom in a committee of the International Civil Aviation Organization has analyzed many hours of radar data tapes and presents good arguments for using a non-uniform distribution, in particular one that would result in more pessimistic operation of TCAS. Until more is known from the analysis of other data, this study will assume such a non-uniform distribution.

SECTION 3

ALTIMETRY

One of the principal features of the earlier work was evaluating the effect that altimetry error would have on the overall safety of TCAS in the ATC system. An essential part of that evaluation was an estimation of the errors in reported Mode C altitude. These errors were estimated based on specifications, regulations, industrial practices, and a meager amount of experimental data. So that, while this information was the best that was available at that time, there remained some doubt as to how well it would represent the altitude data received by TCAS in today's environment. The problem is primarily one pertaining to the many smaller general aviation aircraft that do not fly under instrument flight rules (IFR.) The larger multi-engine aircraft, usually incorporating air data computers, have significantly better altimetry, and all aircraft that fly IFR must have their altimetry systems inspected and calibrated biennially, although some doubt still remains about the accuracy of measurement at high altitudes.[5]

As a result of this situation, the FAA has taken several steps to reduce some of the uncertainty: one is the authorization of a program to collect and analyze data specifically addressed to assessing errors in reported altitude of general aviation aircraft at low altitudes; another is a program to measure altimetry errors at high altitudes; and the third is an investigation of the frequency of "stuck bits" in Mode C altitude encoders. The program to determine the extent of low altitude altimetry errors was performed by a team of engineers from MITRE and the FAA Technical Center; it is reported in Ref. 4. An extensive program of field measurements has been underway for several years by the FAA Technical Center to assess the effects of altimetry errors at high altitudes (Ref. 5.) Finally, an additional effort was conducted by MITRE on an investigation of data from radar tapes to determine the prevalence of encoding errors in reported altitude; the results were published in Refs. 6 and 7.

3.1 MEASURED ALTIMETRY ERRORS AT LOW ALTITUDE

To determine the low-altitude altimetry errors, instrumentation was set up at several airports that handle a large fraction of general aviation aircraft, and data was recorded as the aircraft approached to and departed from the airport. The locations that were selected were the following:

- Atlantic City Airport
- Atlantic City Municipal Airport/Bader Field
- Westchester County Airport
- Teterboro Airport
- Northeast Philadelphia Airport

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[5]Above Flight Level 290, the standard for separating aircraft in altitude is increased from 1000 ft to 2000 ft to account for this uncertainty in altimetry.

A total of 203 operations were recorded; about equally divided between departures and arrivals, and mostly on different aircraft, although there were some repeat data on the same aircraft.

The instrumentation was relatively straightforward. A recording optical theodolite was set up near the runway, and elevation angle was recorded; a spare TCAS unit was set up on the ground near the theodolite to interrogate aircraft in the traffic pattern, and both range and the Mode C report were recorded; a barometer, thermometer, and hygrometer provided the atmospheric data at the recording site. This information was sufficient to measure the geometric altitude of the aircraft, convert it to pressure altitude, and compare it with the pressure altitude that was reported in the aircraft's Mode C reply. Extended readings, over a time interval lasting up to several minutes while the aircraft was climbing or descending, provided the basis for the comparison.

The results of these field measurements and a comparison with the information used in Ref. 1 are shown in Figure 3, which is reproduced from Ref. 4. The earlier System Safety studies used a standard deviation of 118 ft for altitudes below 5,000 ft; the field measurement program found that the measured standard deviation was only 67 ft. On the other hand, it can be seen that the "tails" of the actual distribution are somewhat higher than the ideal Gaussian (Normal) distribution that was assumed, but they are much lower than an ideal "double exponential" distribution. In summary, the errors used in Ref. 1 for low altitudes, it turns out, were quite conservative.

In the calculations that will subsequently be made, these results will be included by using the measured 67 ft standard deviation as the basis for altimetry error in uncorrected systems, but the form of the distribution will be assumed to be double exponential, thereby retaining the conservatism formerly sought, yet accounting for much of the new information that is now available.

3.2 MEASURED ALTIMETRY ERRORS AT HIGH ALTITUDE

In assessing the errors of altimetry at high altitudes (all aircraft above Flight Level 290), the FAA Technical Center has been comparing physical altitudes, measured by an instrumentation radar, with pressure altitude, measured by Mode C replies. Periodic readings of atmospheric pressure obtained by specially instrumented aircraft flying through the field enabled them to convert these readings to Altimetry System Error. While the conclusions are not yet finalized, some early results are available. The standard deviation for all aircraft above Flight Level 290 appears to be about 105 ft, with a distribution that is very close to being "double exponential" (see Appendix F.) In Ref. 1, the value used for altimetry error for general aviation aircraft at an altitude of 30,000 ft was 192 ft, with a Gaussian distribution. While the measured distribution was higher tailed, its smaller standard deviation is a strong compensation in the other direction. As a result, the high-altitude values used in the earlier studies also turned out to be very conservative (see Appendix F), however, no direct use of this fact will be made here.

3.3 IMPACT ON RISK RATIO

The effect that altimetry error has on the Risk Ratio depends on the altimetry error, on the particular strategy that is used for vertical resolution, and on the vertical distribution of aircraft at their

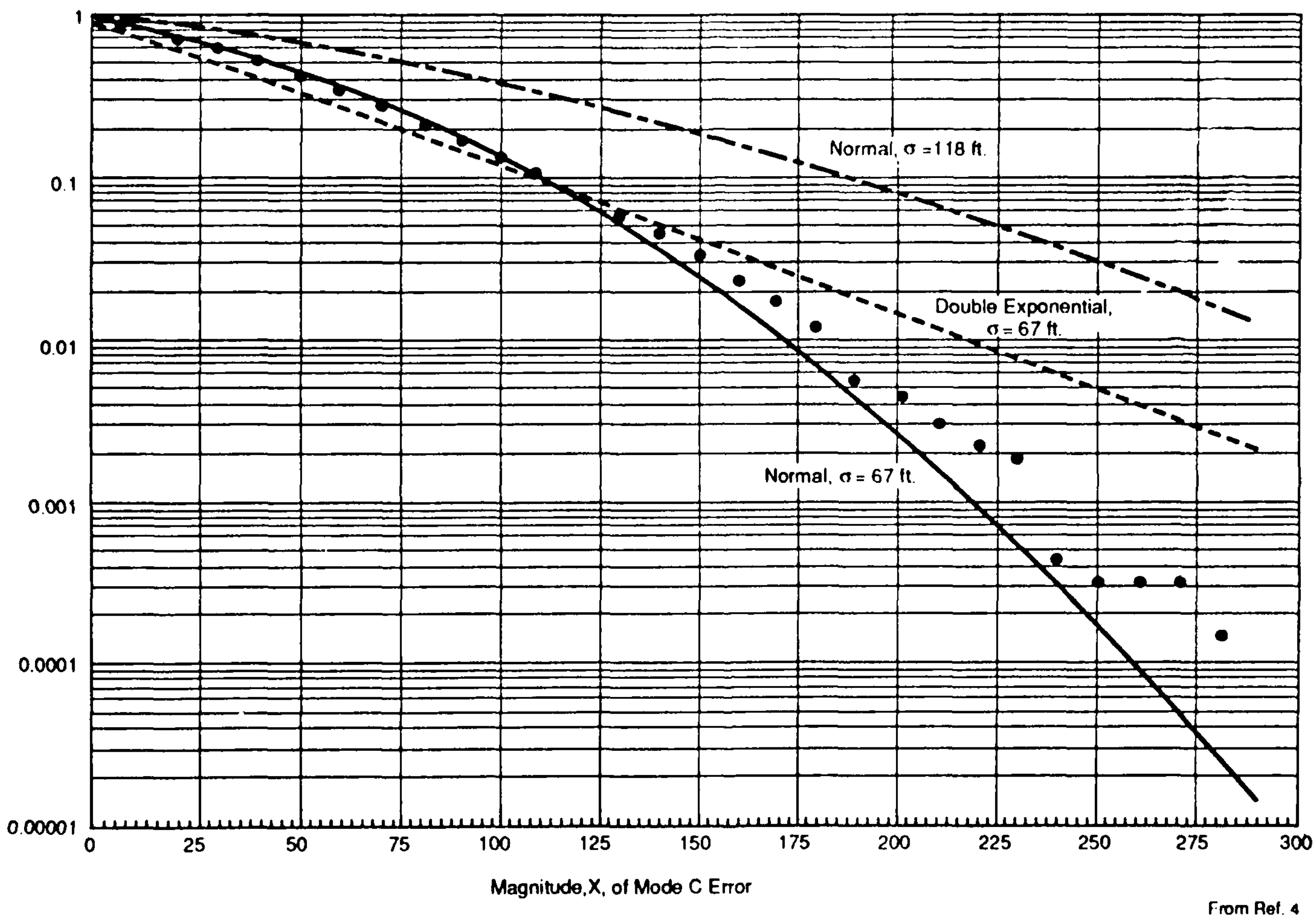

FIGURE 1
MEASURED MODE C ERROR DISTRIBUTION AT LOW ALTITUDES

closest point of approach (CPA). Table 1a compares the assumed standard deviation of altimetry error, both for the earlier studies and for this one, based on the low-altitude tests.[6] For simplicity, the errors are assumed to fol ow the same ratio of increase with altitude, even though the measurements at high altitude show this .o be a pessimistic assumption (see Appendix F).

The modified logic uses a vertical resolution strategy of avoiding crossing altitudes, if at least a separation of the threshold called ALIM is predicted to be achievable; otherwise, the predicted separation is maximized as before. Using these errors and the non-uniform distribution of altitude separation at CPA (Appendix A), the effects of these errors are computed by the numerical integration method used in Ref.1. The results are shown in Table 1b, for the case of achieving maximum separation (non-crossing encounters) and for achieving ALIM separation (crossing encounters). Crossing encounters constitute approximately 14% of all RAs (p 4-39, Ref. 1).[7]

On p. 3-5 of Ref. 1, it was shown that general aviation and "other" aircraft constitute about 79 percent of the critical NMAC incidents involved with an air carrier.[8] Since altimetry for air carriers, which usually have air data computers, is substantially better than that for the uncorrected general aviation aircraft, this value of 79 percent will be used as a weighting factor on the altimetry Risk Ratio, as was done in Ref. 1. One therefore obtains the following end result:

Risk Ratio = Unresolved Component + Induced Component

$$= .79 \times [.0080] + .79 \times [(.0147 \times .86) + (.0370 \times .14)]$$

$$= .006 + .014.$$

$$= .020$$

The comparable values previously computed were not very different—.011 and .014, respectively, which yielded a Risk Ratio caused by altimetry error of .025. Thus, the increase in Risk Ratio caused by the non-uniformity of altitude distribution is just about offset by the better-than-assumed magnitude of altimetry errors.

The final effect on the overall Risk Ratio must include other failure effects as well as environmental factors—these will be brought together later in Section 6.

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[6]As noted in Ref. 1, the value taken for the one-sigma error is the root-sum-square of own altimetry (assumed to be air carrier quality), intruder altimetry (uncorrected general aviation quality), and an estimate of 150 fpm tracking bias error.

[7]With some of the modifications considered in this report, the frequency of crossing maneuvers will be substantially reduced. The prior experience, however, will be used as a conservative estimate.

[8]At high altitudes, this is probably overly conservative, but the relative rarity of NMACs at these altitudes means that the final results will not be so.

TABLE 1
EFFECTS OF ALTIMETRY ERROR

Alt.	ALIM	Fraction of NMAC in Altitude Band	Original RSS Error (1 Sigma) (Gaussian)	New RSS Error (1 Sigma) (Exponential)
5 Kft	400 ft	0.44	143 ft	104 ft
10	400	0.31	156	111
15	500	0.17	175	126
20	640	0.03	190	135
25	640	0.01	206	144
30	640	0.03	220	154
35	740	0.01	239	165

a) Error Assumptions

	Maximum Separation		Take ALIM Separation	
Alt.	Risk Ratio	Weighted Risk Ratio	Risk Ratio	Weighted Risk Ratio
5 Kft	0.0200	0.0088	0.0397	0.0175
10	0.0274	0.0085	0.0536	0.0166
15	0.0231	0.0039	0.0521	0.0089
20	0.0117	0.0004	0.0167	0.0005
25	0.0173	0.0002	0.0245	0.0002
30	0.0251	0.0008	0.0353	0.0011
35	0.0207	0.0002	0.0212	0.0002
	Total=	0.0227		0.0450
	Unresolved=	0.0080		0.0080
	Induced=	0.0147		0.0370

b) Effects on Risk Ratio

3.4 MEASURED ENCODING ERRORS

The third item in the study of altimetry was to obtain a higher confidence for the prevalence of the "stuck bit" condition. That is a situation in which one of the 12 Mode C bits remains stuck on or off well beyond the altitude at which it should have changed. The major impact for TCAS is that if one of the least significant bits, a "C" bit, is the offender, it might go undetected by ATC and yet cause an error large enough to induce an NMAC. This possibility had been evaluated in the System Safety Study using the sparse data available at that time. In connection with the effort to learn more about altimetry errors, MITRE reviewed more than 190 hours of radar data taken in 1981 from the Seattle Automated Radar Terminal System (ARTS III). These results were reported in Refs. 6 and 7. As it turned out, the results were found to be the same as were used in Ref. 1, but now there is a greatly improved level of confidence[9].

The impact that these errors could have is also affected by the new information. As will be seen for some other factors contributing to the induced Risk Ratio, a non-uniform distribution of vertical separation at CPA of the kind now being evidenced would cause an increase by a factor of about 5. On the other hand, the changes in the collision avoidance logic that bias against altitude crossings, as well as those that permit reversals if the encounter continues to degrade, will provide a decrease by a factor of about 10. For this study, the effect of encoding errors on Risk Ratio will be assumed to remain the same as previously (Risk Ratio for encoding errors is .002).

[9] In a recent Working Paper (Ref. 13) very similar results were also reported by a team in the United Kingdom.

SECTION 4

MANEUVERING INTRUDER

When the conflicting intruder aircraft is not TCAS-equipped (it would have only an altitude-encoding transponder), its pilot may inadvertently introduce a maneuver of his own that defeats an escape maneuver by the TCAS aircraft. This only applies if the intruder aircraft does not have TCAS; two TCAS aircraft will by design always have coordinated, complimentary maneuvers posted. The primary concern is for situations in which an altitude crossing is predicted. This can be broken down into two cases: intruder crossing a level TCAS, and TCAS crossing a level intruder. Means for coping with these situations are discussed in the following subsections.

4.1 INTRUDER CROSSING A LEVEL TCAS

To compare results of alternative collision avoidance logics, it is necessary to estimate the hazard introduced by a suddenly maneuvering intruder. Two different methods have been used in the two previous studies. The method used in the original System Safety Study will be used here; it is based on data from the Piedmont Phase I flights, it is easier to apply, and at the same time it is the more conservative approach.

The principal safety consideration is for encounters in which the intruder has a substantial vertical rate and is projected to cross the altitude of the TCAS aircraft, as in Figure 4. When the conditions for issuing an RA are satisfied, the current collision avoidance logic estimates the results of an escape maneuver by assuming that the TCAS aircraft will, after a 5 second delay, start a 1/4 g acceleration to a rate of 1500 fpm.[10] It chooses either the climb sense or the descend sense, depending on which would give the greater predicted separation at CPA. In this case, a descending maneuver by the TCAS aircraft would result in the greater separation, provided the intruding aircraft continues its current vertical rate. However, that solution could be foiled by a sudden intruder maneuver, most commonly a level-off. Once selected, the current logic does not change the sense of the RA; however, the strength of the RA does change to whatever degree is appropriate, within limits.

If the intruder should make a maneuver that thwarts the TCAS escape maneuver, the TCAS logic waits until it is confident of this fact and then posts an Advisory Invalid message. Upon receipt of that message, the TCAS pilot is instructed to procedurally return to his previous altitude, since it is now known that the posted RA is no longer effective and may even be hazardous. Ref. 1 made estimates of the frequency of a hazardous level-off, using data from the Piedmont Phase I flights; no accounting, however, was made for the pilot returning to his previous altitude on receipt of the warning.

[10] The parameters used in these calculations are really a "mathematical fiction" intended to delineate the achievement of an altitude displacement of about 400-800 ft.

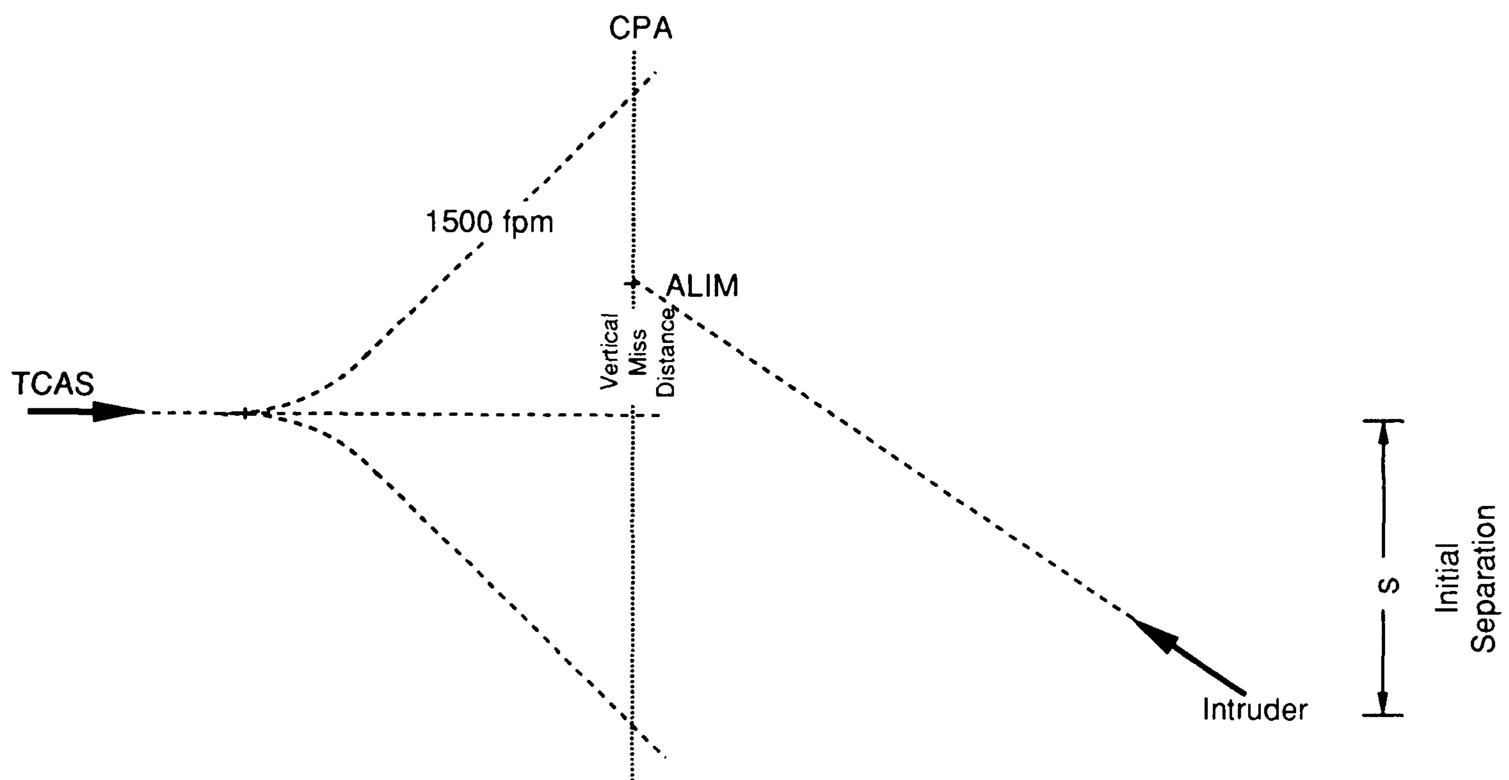


FIGURE 2
ALTITUDE CROSSING ENCOUNTERS

Since the major failure is for encounters in which an altitude crossing is predicted, modifications to the collision avoidance logic were explored in order to cope better with this eventuality. As previously stated, one modification was to add logic that would avoid the crossing, provided that a predicted separation of ALIM or greater is achievable in the non-crossing direction.

A further modification to the logic would first detect whenever a quickly deteriorating situation exists, and then post a reversed-sense RA to the TCAS aircraft. In a majority of such instances, it will be seen that there is sufficient time for the TCAS aircraft to reverse itself and avoid an NMAC. The key to an effective reversal, however, is prompt detection and reaction.

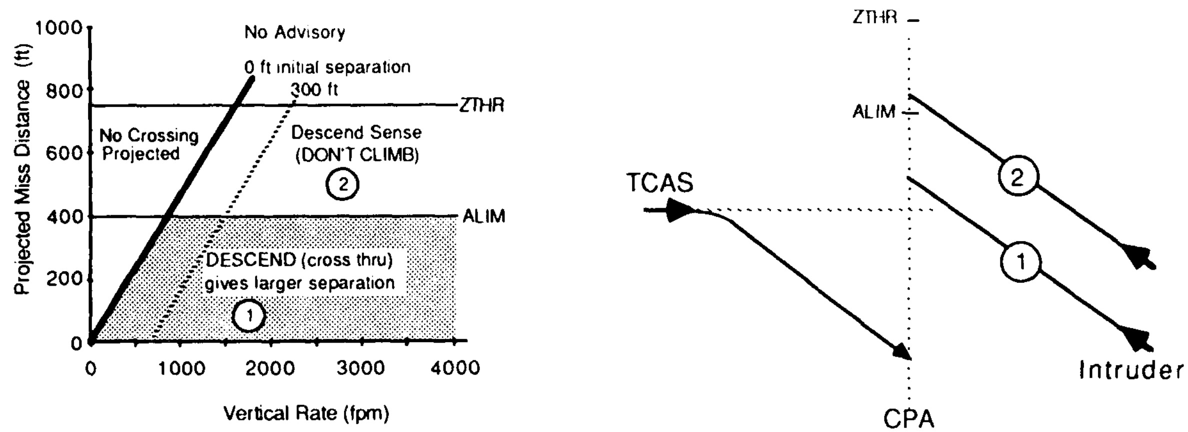
A third modification would avoid the issuance of a crossing advisory if the aircraft are within the minimum altitude separation usually imposed by ATC (i.e., 1000 ft). This would insure compatibility with the common procedure of levelling off aircraft so that they will pass with this separation, and yet it would provide some time (albeit minimal) for escape if the intruder inadvertently continues to hold his vertical rate. This suggestion was found, in an analysis by the United Kingdom, to remove a substantial number of RAs that would subsequently have produced an Advisory Invalid indication (current logic) or would have had to be reversed (modified logic). Infrequent reversals might be tenable; frequent ones would not.

The following subsections will estimate the Risk Ratios caused by suddenly maneuvering intruders, first for the current logic, and then for the modified logic.

4.1.1 Current Logic

The shaded area in Figure 5a illustrates the region for which a level TCAS can be "faked out" by a climbing intruder suddenly levelling off (a similar region exists for a descending intruder). To the left of the dark slanting line as well as below the abscissa, the two aircraft will not cross in altitude; above the upper horizontal line, the projected separation is sufficiently great that no RA is given. These concepts are illustrated by the geometrical situations numbered in Figure 5b, and indicated by similar numbers in Figure 5a.

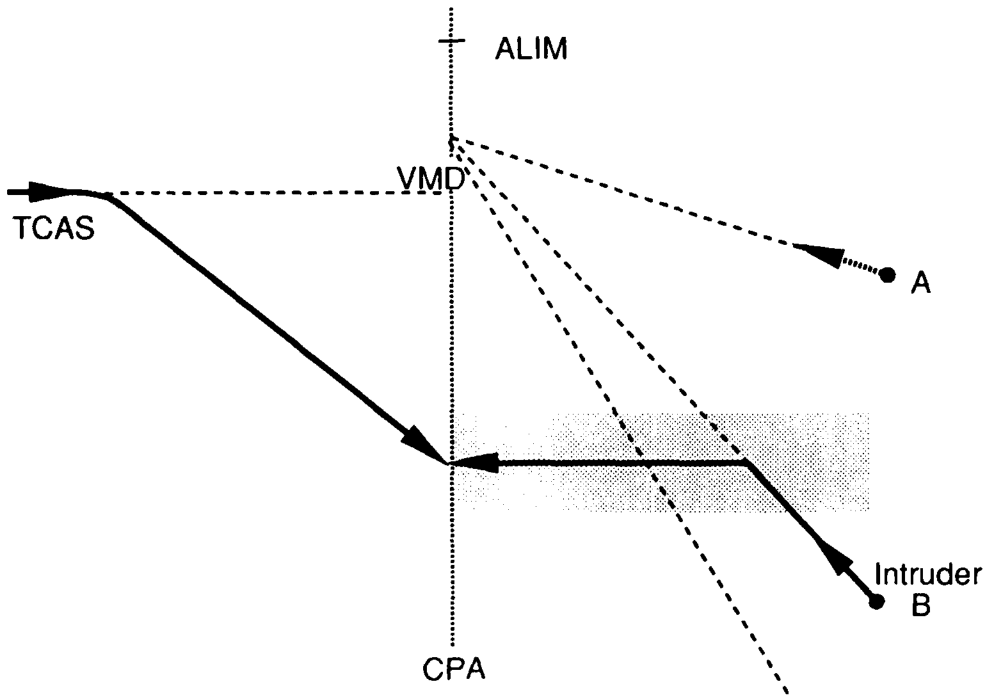
Figure 6 shows the approach used to calculate the Risk Ratio for the maneuvering intruder. A level TCAS aircraft at the time of the RA is represented at the left side of the Figure; several intruders climbing at different rates are represented on the right. Intruder A constitutes no special hazard (indicated by a dotted arrow) as it is above the altitude to which the TCAS aircraft will maneuver, and a level-off by the intruder poses no unusual threat. Intruder B will cross the destination altitude of the TCAS aircraft. If the intruding aircraft continues on, the TCAS aircraft will have made a proper escape. If the intruder levels off within 100 ft of the TCAS aircraft's altitude at the closest point of approach (shaded region), an NMAC will occur, provided simultaneous horizontal proximity also exists. Intruder C also will have the potential for a similar failure (both of these are indicated by solid arrows). The histogram at the far right of the Figure shows roughly the vertical rate distribution measured from the Piedmont Phase I program; many more altitude crossing intruders would be encountered in the vicinity of A than in the vicinity of C.



a) Region of Level-Off Susceptibility

b) Geometrical Situations

FIGURE 3
REGIONS OF SUSCEPTIBILITY TO MANEUVERING INTRUDER
(CURRENT LOGIC)



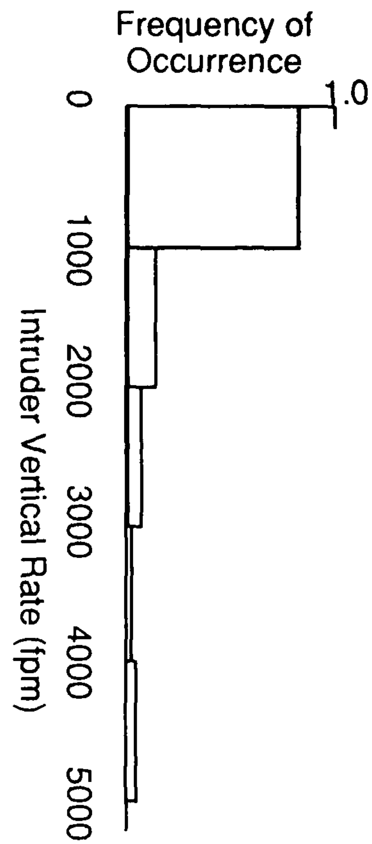


FIGURE 4
MANEUVERING INTRUDER
(CURRENT LOGIC)

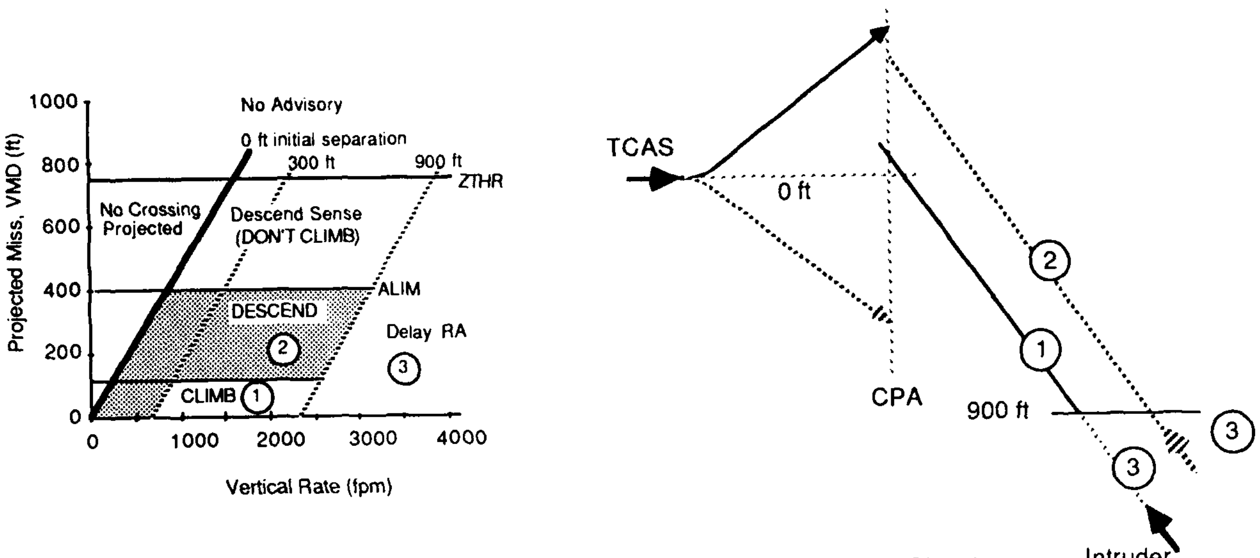
The potential of an NMAC would be turned into a real NMAC only if the intruder actually does level off in the critical altitude band (or time window) indicated by the shading of Figure 6. The whole calculation was carried out in Section 4.3 of Ref. 1.

4.1.2 Modified Logic

For the modified logic, Figure 7a presents as shaded the region in which a level TCAS is susceptible to a climbing intruder suddenly levelling off. As compared with the current logic, there are several regions of intruder vertical rates and projected miss distances for which the level-off is no longer a threat. One of these is where the vertical miss distance is relatively small, so that ALIM separation can be achieved by a non-crossing TCAS maneuver. This is depicted in Figure 7b by the solid lines (for intruder position 1). For the intruder in position 2, ALIM separation cannot be achieved by the non-crossing sense, so the crossing maneuver is chosen, as shown. The exception to this latter statement, shown by intruder position 3, is when the initial separation is greater than the usual minimum ATC separation (illustrated as 900 ft in the Figure). As noted earlier, the issuance of a crossing maneuver under these conditions may well conflict with a forthcoming ATC action; avoiding the issuance of such an RA will avoid the possibility of inducing an NMAC, although, if the intruder blunders on, there are some high altitude-rate encounters that may not be capable of resolution.

The basis of the calculation is illustrated in Figure 8. The situation differs from that created by the current logic, in that once the intruder starts to level off, and his projected altitude at CPA drops below the *current* TCAS altitude, it is considered safe and proper for the TCAS aircraft to reverse itself and start a climb. (The reversal would not be instituted, however, if the altitudes of the two aircraft were within 100 ft of each other when the level-off occurs, because it takes nearly 100 ft for the TCAS aircraft to reverse itself. Neither will a reversal be called for if the modeled response of the TCAS aircraft, using the maximum bound on intruder's vertical rate, cannot obtain clearance.) A further restriction is shown by an intruder in position A of Figure 8. This would not result in an NMAC, because the RA is first generated when the aircraft are initially close vertically (within 300 ft), so no reversal would be permitted; the TCAS aircraft would continue to descend. The aircraft in position B could pose a hazard, but, as shown, there is sufficient time for the TCAS aircraft to reverse itself and get clear, even if the intruder levels off just as it closes to 100 ft away from the TCAS altitude. An earlier level-off would provide even more separation; a later level-off would result in the TCAS aircraft continuing on through without reversing, again providing more separation. The aircraft in position C, climbing at a higher rate, could pose a hazard, as there may not be sufficient time for the TCAS aircraft to get clear by reversal, if a level-off comes as the intruder closes to 100 ft away from the current TCAS altitude. This is especially true if, as assumed here, these crossing RAs are not issued unless the aircraft are within 900 ft of each other's altitude.

The process is detailed in Appendix B, where an estimate is made of the separation achievable when the modified logic calls for a reversal. The calculations assume a pilot delay of 2.5 seconds (compared with 5 seconds for the initial maneuver) and a vertical acceleration of 1/3 g to 1500 fpm (compared



a) Region of Level-Off Susceptibility

b) Geometrical Situations

FIGURE 5
REGIONS OF SUSCEPTIBILITY TO MANEUVERING INTRUDER
(MODIFIED LOGIC)

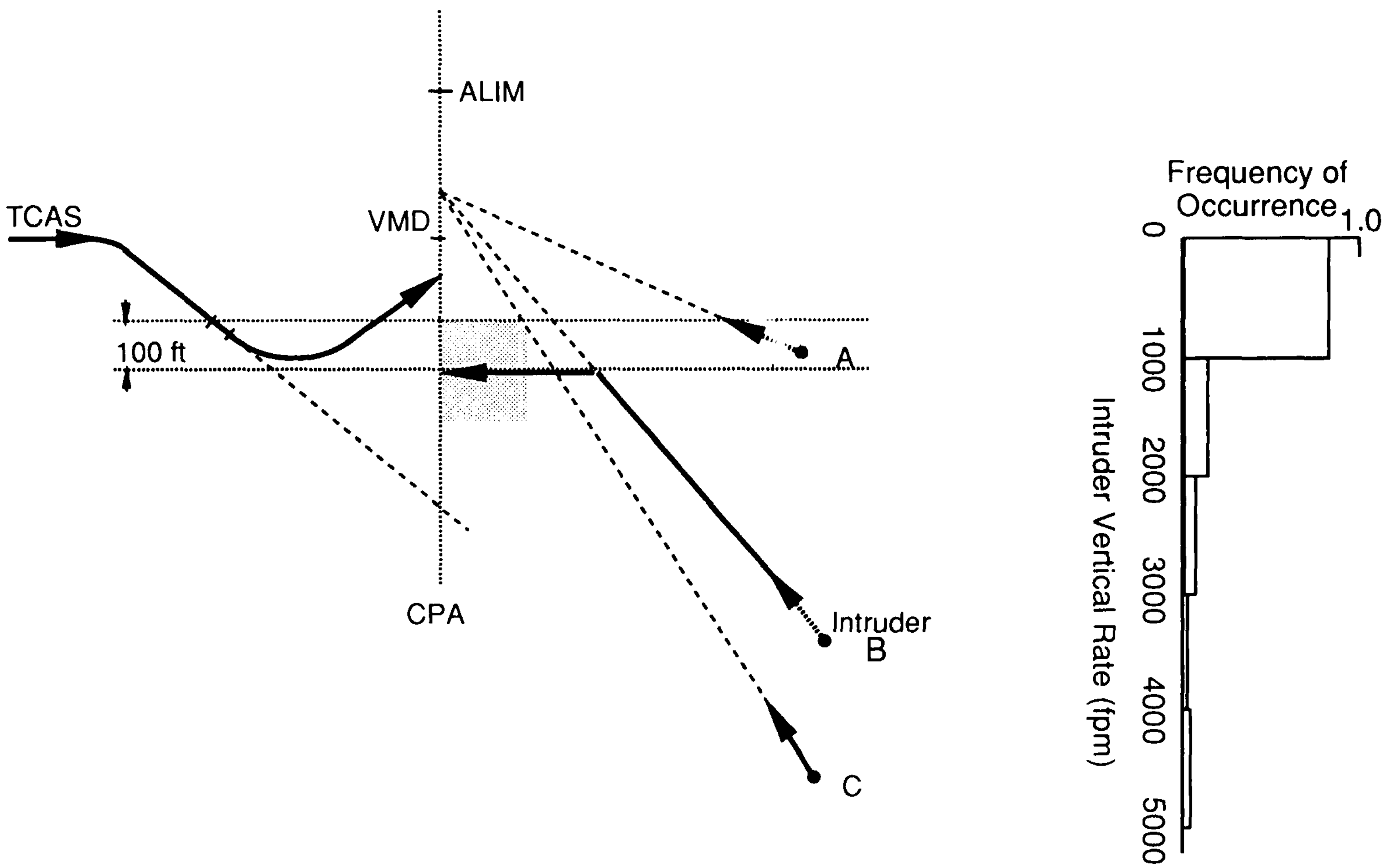


FIGURE 6
MANEUVERING INTRUDER
(MODIFIED LOGIC)

with 1/4 g to 1500 fpm for the initial maneuver). These values, used to calculate the probability of being able to avoid an NMAC with a reversal, are intended to represent an expeditious pilot reaction.[11]

Using the data supplied by the UK (see Appendix C), the expected impact of maneuvering intruders on the RAs are summarized in Figure 9. All RAs are represented by the large square as well as by the tabulation; they occurred approximately once in every 40 hours of flight (.025 probability) in the Piedmont Phase I experience. It was shown on p. 4-39 of Ref. 1 that in about 14 percent of the RAs, an altitude crossing is projected; this is indicated by the largest circle and the corresponding tabulation. Appendix D estimates the frequency that reversals will be required—approximately 6/10 of one percent of all RAs (4 percent of the ones for which a crossing is projected). Again, these are indicated in Figure 9.

Only a very few of those encounters for which a reversal is posted would result in an NMAC; they must also come within 100 ft vertically and about 500 ft horizontally. Figure 9 shows all crossing encounters that are estimated to come within 100 ft vertically because of a sudden intruder maneuver, and then shows the fraction of those that are also NMACs (close horizontally); these are indicated in the Figure by the blackened portion of the small NMAC area.

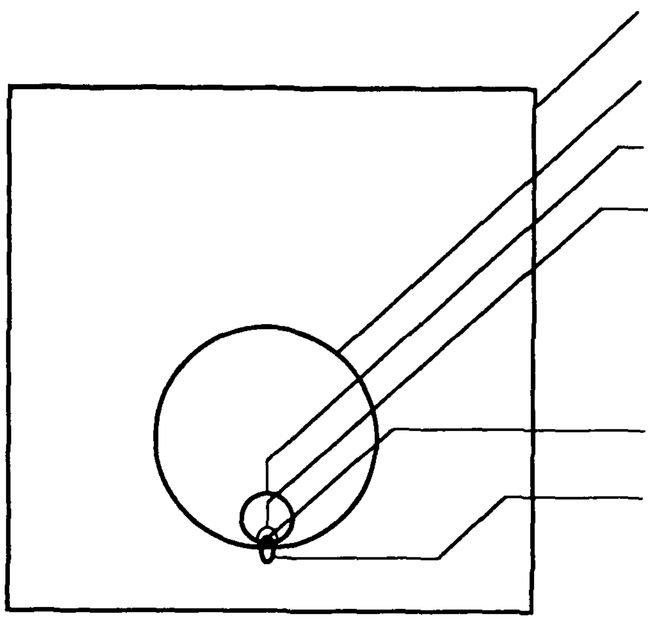
The quantitative value for induced Risk Ratio is determined from the current level of NMACs. For TCAS to induce an NMAC, it must, of course, generate an RA. Appendix A shows that about 1/50 of all RAs will be for aircraft that, in the absence of TCAS, would come within 100 ft vertical separation. If additionally any of them are also close laterally, that would define an NMAC in today's situation, without TCAS. Thus one can first multiply the current rate of NMACs by 50 to obtain the set of RAs that would be candidates for inducing an NMAC. Then one can multiply that by the computed probability that the intruder might level off and end up within 100 ft of the altitude of the TCAS aircraft (shown in Appendix C to be .00032). The result is 50 x .00032, or .0155.

It may be remembered from Ref. 1 that the corresponding Risk Ratio for the maneuvering intruder was estimated to be .027. Thus, the degradation in TCAS performance caused by the non-uniform distribution of vertical separations is more than compensated by the new collision avoidance logic that explicitly permits a reversal when needed.

As Figure 9 reiterates, the pre-existing probability of an NMAC is about 10^{-5}. The net probability of an NMAC caused by a suddenly maneuvering intruder would then be the product of .0155 and 10^{-5}, or 1.6×10^{-7}. Figure 9 is drawn roughly to scale; the tabulation, however, gives the numerical results.

As noted earlier, the key to a successful reversal maneuver is prompt detection and reaction. The detection rule used for the reversal is considerably more responsive than the rule that was necessary for

[11]These values were arrived at in cooperation with Special Committee 147 of the Radio Technical Commission for Aeronautics.



Description	Fraction of RAs	Prob/Hr	Hr/Event
All RAs	1.00	2.5E -2	40
Crossing Projected	0.14	3.5E -3	290
Reversal	0.006	1.5E -4	6,700
Intruder Maneuvers to < 100' Vertically	3.2E-4	8.0E-6	125,000
NMACs Induced by Maneuvering Intruder	6.4E-6	1.6E-7	6,250,000
All NMACs	0.0004	1.0E -5	100,000

x 50=Risk Ratio (.016)

FIGURE 7
BREAKDOWN OF RESOLUTION ADVISORIES
(MODIFIED LOGIC)

the Advisory Invalid logic. Similarly, the pilot reaction noted above, is predicated on pilot awareness of the situation and its potential, through training, the TA display, and a feature in the logic that annunciates a crossing maneuver.

To validate the calculations, a simulation was run using the vertical tracker, the actual algorithms of the logic, and various vertical rates. Even for a hard-to-detect deceleration of 1/8 g, the simulation provided somewhat more time for reversal than this calculation, which used an artificially infinite deceleration.[12] Thus, in an overall sense, these results are conservative, even though a specific encounter may not be exactly represented.

4.2 TCAS CROSSING A LEVEL INTRUDER

A crossing encounter in which the intruder is level and the TCAS aircraft has a vertical rate is shown in Figure 10. Those combinations of vertical rate and projected miss distance for which the current logic would advise a climbing TCAS to cross through the altitude of the intruder in achieving the greatest separation are shown by the dark shaded region in Figure 11a. Except for a small region that includes relatively high vertical rates, a crossing would be required only when the aircraft are initially within about 300 ft of each other—a condition that is not at all objectionable. The modified logic described above ("Do not cross altitude if ALIM separation can be achieved") has the effect of removing the region of high vertical rates and large initial separations, as illustrated in Figure 11b. The result is to avoid the possibility of calling for the TCAS aircraft to maintain a momentarily high vertical rate just to cross clear of the intruder, and also, as will be shown later, to provide an advantage in TCAS-to-TCAS encounters when flying IFR in the ATC system.

4.3 NON-CROSSING ENCOUNTERS

In the current logic the Advisory Invalid indication is used to signal any situation in which the effectiveness of the RA becomes seriously degraded, not only the one situation of major concern, the level-off. So if the Advisory Invalid feature is to be removed, some other provision must be introduced to handle those instances in which the intruder may increase his rate so as to degrade the RA. Such a feature has been included; when a non-crossing RA degrades sufficiently, the TCAS aircraft will be told to increase its vertical rate beyond the nominal 1500 fpm, or beyond the current rate if it already is greater than 1500 fpm. With this feature, it then becomes feasible to entirely eliminate the Advisory Invalid indication for handling maneuvering intruders.[13]

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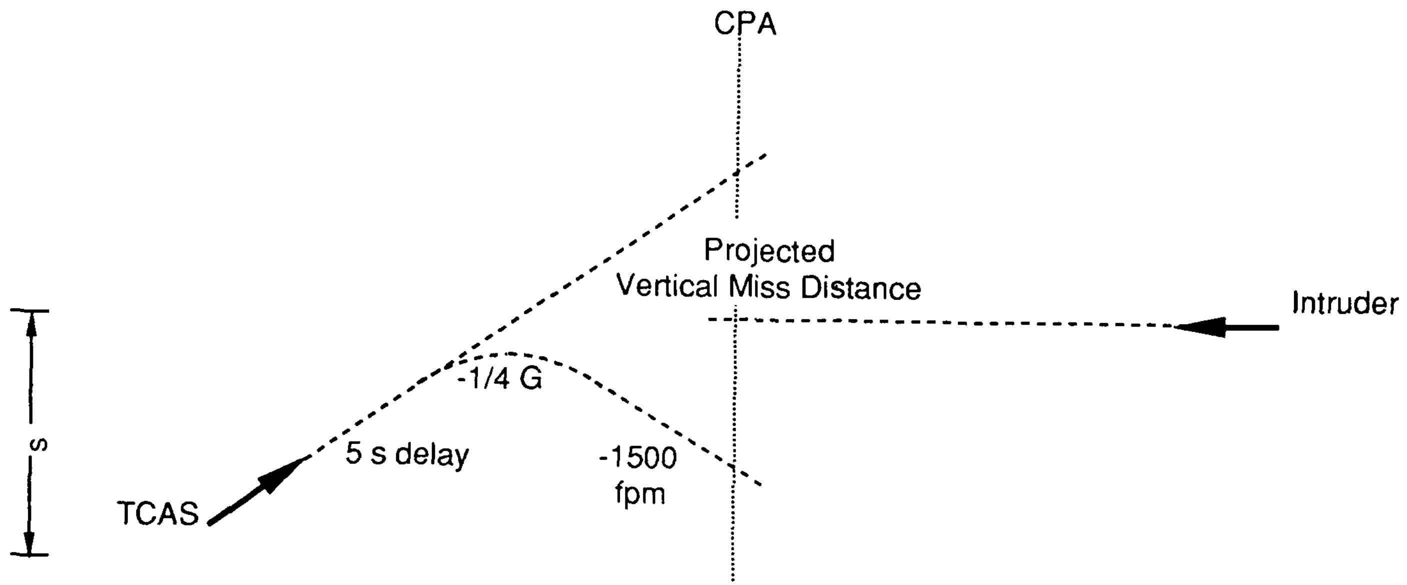
[12] The actual "worst altitude" in a real situation would be somewhere between those illustrated in Figure 6 and Figure 8, depending on tracking lags.

[13] There is one other condition for which the Advisory Invalid feature is used in the current logic; that is to annunciate the remote possibility of an incompatible RA being issued against another TCAS aircraft. Should that ever happen, the modified logic would have the aircraft with the higher Mode S identifier reverse the sense of its RA. The resulting failure probabilities for this condition are then well below those given in even the most restrictive of the certification tolerances (See Appendix G and Ref. 8).



s = Separation at Time of Resolution Advisory

FIGURE 8
ALTITUDE CROSSING WITH A LEVEL INTRUDER

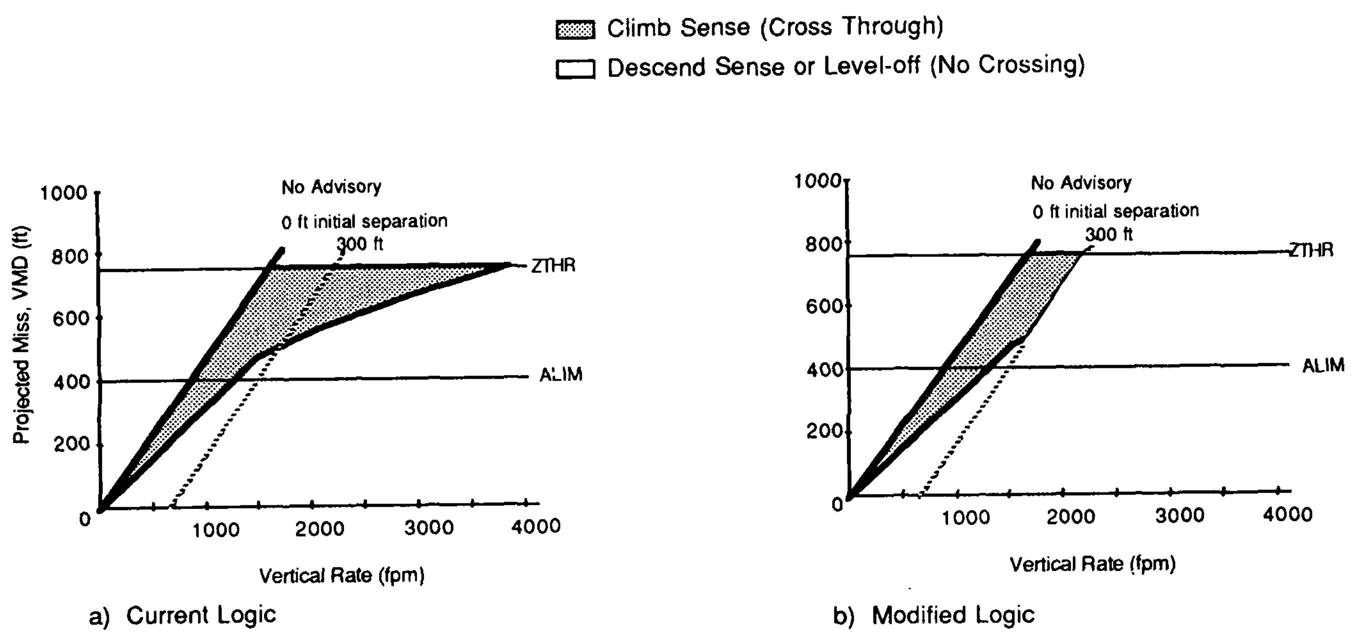


FIGURE 9
REGIONS OF ALTITUDE CROSSING FOR LEVEL INTRUDER

SECTION 5

EFFECTS OF PROPOSED FAA RULEMAKING

A major factor in favor of TCAS is the fact that no special equipment is necessary for the other aircraft—only the conventional ATC transponder with a Mode C altitude encoder (a substantial, but lesser, safety benefit still exists even if the intruder only has a transponder and not an altitude encoder). A further benefit can be expected if all air carrier aircraft are TCAS equipped.

This latter benefit occurs simply because TCAS substantially reduces the probability of an NMAC for each aircraft on which it is carried. If all air carriers had TCAS, as is contemplated in a current Notice of Proposed Rule Making, or NPRM, the total annual NMACs for air carrier aircraft would be effectively reduced by the net Risk Ratio for each of these aircraft. The individual Risk Ratio for any particular TCAS-equipped aircraft, however, would only be affected in a minor way. This is because NMACs between air carrier aircraft constitute only 9 percent of the cases, and air carrier aircraft with their air data computers mostly have corrected altimetry. The real benefit would be to minimize any failures caused by maneuvering intruders; however, conflicts between aircarrier aircraft are coordinated by design. Nevertheless, the highest level of protection against a conflict between two air carrier aircraft, though not measurable in terms of significant probabilities, would thereby be provided.

Another NPRM (Ref. 10) requires the carriage of Mode C transponders by all aircraft above 10,000 ft. MSL[14], or within 30 nmi of the principal airport of a Terminal Control Area (TCA) or a Terminal Radar Service Area (TRSA). To give some idea as to the effectiveness of such action in relation to TCAS, the location of recent NMACs was investigated. The FAA provided this information on the 53 critical NMACs, involving at least one air carrier, that occurred within CONUS in 1986. It was found that 38 (70 percent) were either within 30 nmi of the principal airport of a TCA or TRSA, or else they were above 10,000 ft.

Thus 70 percent of all NMACs would be covered by the Mode C rules. It is assumed that the current transponder and Mode C equipage probabilities[15] would apply to the remaining 30 percent.

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[14] The present requirement is 12,500 ft.

[15] Ref. 1, p. 3-9, showed that for the other aircraft encountered in NMACs, 92 percent were equipped with transponders, 61 percent were equipped with Mode C encoders.

SECTION 6

UPDATED RISK RATIO

The Risk Ratio, an estimate of the change in the risk of an NMAC brought about by the use of TCAS, depends on altimetry error, the specific collision avoidance logic, and the environment of aircraft in the airspace that TCAS encounters. Section 3 showed that all the information that has become available since the original System Safety Study in 1983 tends to leave those original results relatively unmodified. Thus, even though there is now evidence that the vertical distribution of aircraft in crowded terminal airspace would degrade the performance of TCAS, there is offsetting evidence that the former assumptions regarding altimetry errors were too severe, and the collision avoidance logic has been made considerably more robust to the consequences of that distribution.

Figure 12 shows the elements that summarize the original System Safety Study of Ref. 1 ("overall" weather conditions, present-day level of transponder and Mode C equipage, TAs provided on non-Mode C aircraft as well as on Mode C aircraft). The bar in the center represents the current probability of a critical NMAC without TCAS, a Risk Ratio of unity. The shaded bar to the right of the central reference represents the maximum fraction of induced NMACs that could be caused by the errors previously discussed—C-bit encoding errors, altimetry error, and maneuvering intruders. In Ref. 1, the calculations for these maximum values were .002, .0174, and .027, respectively as shown. These maximum values, or basic calculations, must be modified by the factors noted in order to arrive at a final value for induced Risk Ratio. For example, the maximum effect of altimetry errors is reduced by the fraction of general aviation aircraft actually in the system; all three components—encoding errors, altimetry errors, and maneuvering intruders—must be reduced by the fraction of non-transponder, and in this case, non-Mode C aircraft in the system, and by the small probability that the surveillance function may not have the intruder in track when it is needed (these errors, however, will show up later as "unresolved" NMACs rather than here as "induced" NMACs). Then, finally, all three elements must be reduced by the likelihood that visual acquisition, as aided by the TA display, will occur in a timely manner. All of these factors were estimated in Ref.1 and amounted to an induced Risk Ratio of .011.[16]

The left side of Figure 12 represents the relative fraction of unresolved NMACs, where TCAS would not be effective. (Incurring an NMAC with a non-transponder intruder is a prime example.) The maximum effect of altimetry error in this case is indicated as a Risk Ratio of .0143, which is reduced

[16]The final values from Ref. 1, shown in Figure 12 as .0004, .0035, and .007 for C-bits, altimetry, and maneuvering intruders, are slightly modified in this report to .0005, .0036, and .0072 to correct for round-off differences, and to place the comparisons between logic versions on the same basis.

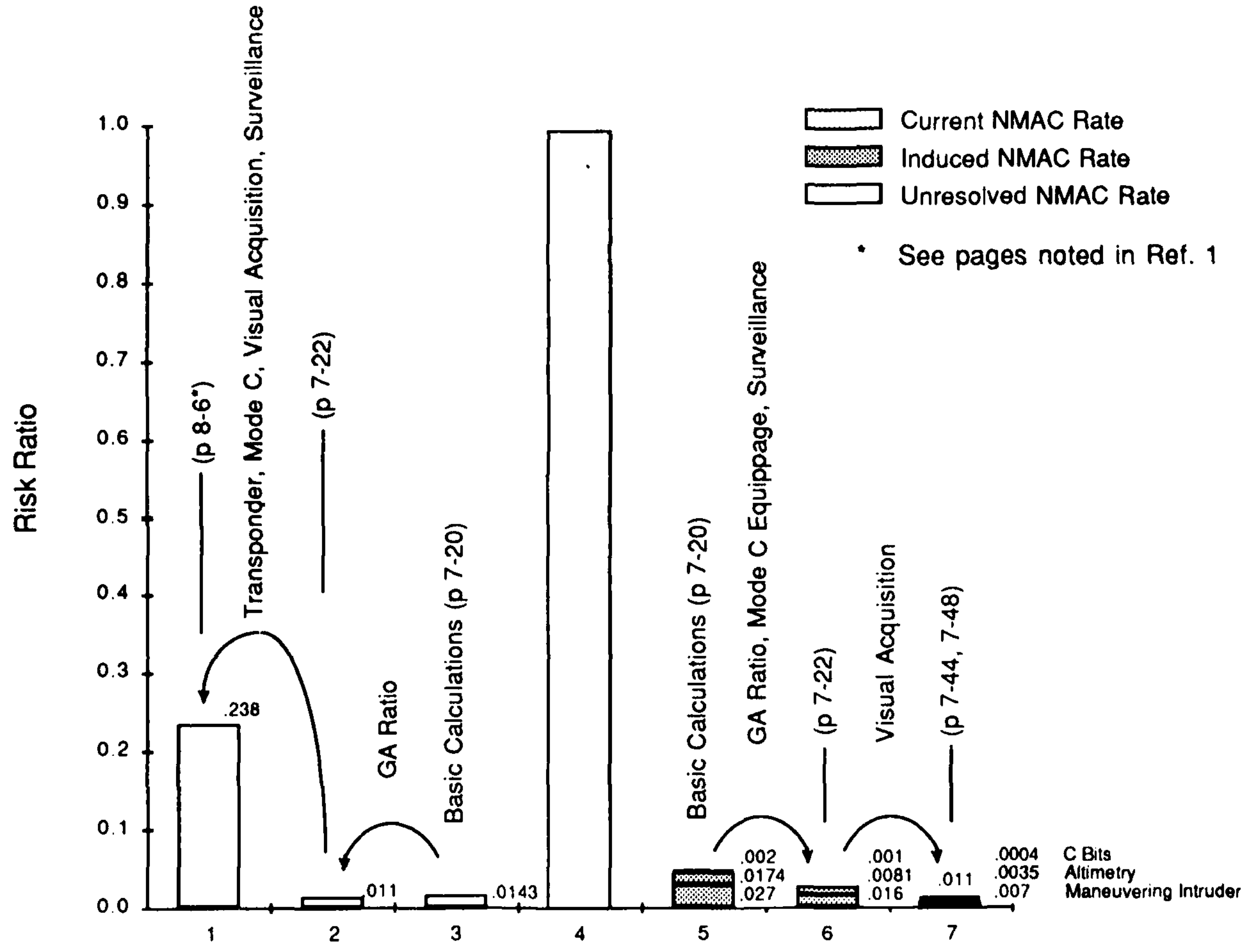


FIGURE 10
DEVELOPMENT OF RISK RATIOS

by the fraction of general aviation aircraft encountered. The large increase indicated by the left-most bar is principally caused by the lack of universal equipage with transponders and Mode C encoders.[17]

In Figure 12, page numbers of Ref. 1 are given where the appropriate values may be found, thus acting as a "road map" to that study, helping the interested reader pick his way through the analysis. Appendix H offers the same analysis with a different presentation. This method of presentation is then carried out for the modified logic in several postulated environments.

Section 5 provided an approach to determining the effect of the Mode C NPRM. The approach is to say that aircraft in all but 30 percent of the NMACs would be in airspace where they would be required to carry Mode C transponders. For overall conditions, the remaining equipage would follow the overall equipage statistics previously determined—92 percent have transponders, and 61 percent have Mode C encoders. That works out to a total probability of transponders as follows:

Intruder has transponder = (1.0 x .70) + (.92 x .30) = .98

Intruder has Mode C encoder = (1.0 x .70) + (.61 x .30) = .88

Table 2 shows the results for the original study of Ref. 1, for this study using today's Mode C equipage, and for this study using the estimate of Mode C equipage for the NPRM being effective.

Up to this point, nothing has been said about operation in IMC. Ref. 2 examined the aircraft environment and the airspace practices in IMC explicitly to assess any effect that might be pertinent to operation with TCAS. Several things were found to be different from the more common "overall" conditions. First, the fraction of aircraft encountered that are Mode C equipped is higher by one-third, and the fraction that are air carriers (and carry high-quality altimetry) doubles; this alleviates somewhat the effects of altimetry errors. Second, the structure of the airspace and the common practices under those conditions also alleviates somewhat the effects of the maneuvering intruder. The net result was that, despite the assumption that visual acquisition would be completely ineffective, failures, both induced and unresolved, were lower in IMC than otherwise. Since these same factors still apply, the same conclusions are reached—TCAS performance in IMC is at least no worse, and probably somewhat better, than in overall conditions. No new data, however, is available to provide an updated quantitative assessment.

[17] In Ref.1, the value of the unresolved Risk Ratio when TAs on non Mode C transponder aircraft were displayed was estimated to be .238 ; it is more properly .243, which is the value used in this report.

TABLE 2
EFFECTS OF MODIFIED LOGIC

OVERALL CONDITIONS

	Induced	Unresolved	Total
Original Study	.011	.243	.254
Modified Logic	.009	.242	.251
Modified Logic and Mode C NPRM	.012	.094	.106

SECTION 7

ATC INTERACTION

In addition to evaluating the quantitative safety implications, it is also important to understand any impact that TCAS may have on the normal interaction of the aircraft flying IFR within the ATC system. Among other things, the earlier IMC study (Ref. 2) addressed the potential for TCAS to cause a "domino effect" in dense regions of traffic, as well as for any tendency to disrupt aircraft flying on a parallel approach to an airport. Subsequent to that study, concern has been raised over the possibility for TCAS to disrupt other situations in which both aircraft are flying normally ("by the rules"). After reviewing the results of the earlier work, two new situations will be addressed: encounters between two TCAS aircraft, in which one is transitioning in altitude; and encounters between a level TCAS aircraft and an unequipped aircraft that is transitioning in altitude.

7.1 REVIEW OF IMC STUDY

In both an evaluation of high-traffic-density radar data, where the aircraft were in a holding pattern, and in an analysis of an artificially "compacted" holding pattern, it was found in Ref. 2 that a TCAS RA would bring a deviating aircraft back to its clearance without any tendency toward creating an unstable situation, such as generating a domino effect. In fact, the multi-aircraft TCAS logic appeared to prevent movement from propagating to additional aircraft. That study also showed that for the traffic samples as provided by the ATC radar tapes, all of the aircraft that would have received RAs would have passed within 3 nmi and 1000 ft (IFR separation standards).

Another major concern addressed in Ref. 2, the parallel approach question, also produced similar results. That is, an RA only occurred if the vertical separation was too small too early in the approach. Following the aircraft tracks from the radar data, one could also observe that the aircraft did indeed correct their vertical profiles at about the same time that they would have received an RA.

Many other factors are addressed in Ref. 2, such as alert rates per controller, workload factors, and others; the interested reader is encouraged to review that document directly.[18]

7.2 TCAS-TCAS ENCOUNTERS

In Section 4.2, it was shown that, even for a projected crossing encounter against a level intruder, a TCAS aircraft that was climbing or descending would reverse itself naturally and avoid crossing the intruder's altitude in the great preponderance of cases, especially for the modified logic (Figure 11b). In a meeting of the Secondary Surveillance Radar Improvement and Collision Avoidance System Panel (SICASP) of the International Civil Aviation Organization, it was brought out that this type of

[18]The average rate at which an aircraft controlled by a Chicago Terminal controller would receive a corrective RA is once every 6 hours, assuming *all* aircraft equipped with TCAS. RAs requiring a displacement of more than 300 ft would have occurred once every 19 hours on the average.

encounter could either naturally fit in with ATC practice or introduce some awkward maneuvering, depending on which of the two TCAS aircraft were to go first. That is, if, in a crossing encounter between two TCAS-equipped aircraft, the TCAS aircraft having the vertical rate detects the conflict first, it would most likely generate an RA that called for reducing or reversing its current rate, leaving the level TCAS aircraft essentially undisturbed, which in all likelihood was the ATC intention. On the other hand, if the level TCAS aircraft were the first to detect the conflict, it would be more likely to cross the intruder's altitude. Since both aircraft in this scenario are TCAS equipped, there is no danger of an uncoordinated action, as there might be if this were not the case, but it is highly unlikely that the intention of ATC is to set up such an encounter. Thus, there is a chance that a late ATC solution might be contrary to the TCAS solution.

The suggestion was made in Ref. 11 that some means be taken to force the level TCAS to defer to the one having a substantial rate. This concept is included in the modified logic, where, in a crossing encounter, a substantially level TCAS (less than 600 fpm) will defer to a TCAS with a vertical rate (greater than 600 fpm) for an interval up to 3.5 seconds. If the TCAS with the vertical rate does not detect the encounter and start the coordination process by that time, the level TCAS aircraft will proceed on its own. These features in the modified logic enhance the compatibility of TCAS with the ATC system.

7.3 FORCED ALTITUDE DISPLACEMENTS

A concern that has been raised is the possibility that a transitioning intruder might introduce a degree of disorder into the normal flow of traffic by causing frequent, large deviations of a level TCAS aircraft from its altitude clearance. Of course, if there is a real conflict and the aircraft are within the ATC separation standards, TCAS would be expected to provide an alert; it is just when all aircraft are following the rules and are properly separated that the concern exists. The cause for the concern can be shown by referring to Figure 13. The TCAS aircraft is level on its cleared altitude. An intruder is climbing toward it at a high rate and levels off at its own clearance, 1000 feet lower. What will happen?

The answer depends on the intruder's altitude rate (V), the projected miss distance (VMD), and the collision avoidance logic. If V is great enough, and VMD is within ALIM, TCAS will post a corrective RA, which will last until the intruder levels off at his own clearance, or until the the TCAS aircraft moves to achieve ALIM + 75 ft separation. After such action, the RA will downgrade and the TCAS aircraft will level off, thereby displacing approximately another 100 ft before it returns to its original altitude.

The displacement of the TCAS aircraft off its clearance by this TCAS-induced action is estimated in Appendix E. This displacement increases as ALIM increases, so the effect is most noticeable at higher altitudes where ALIM is large; the calculations are conducted for the parameters of the 18-30 thousand foot range. Using the distribution of vertical rates observed in the Piedmont Phase I Program, the

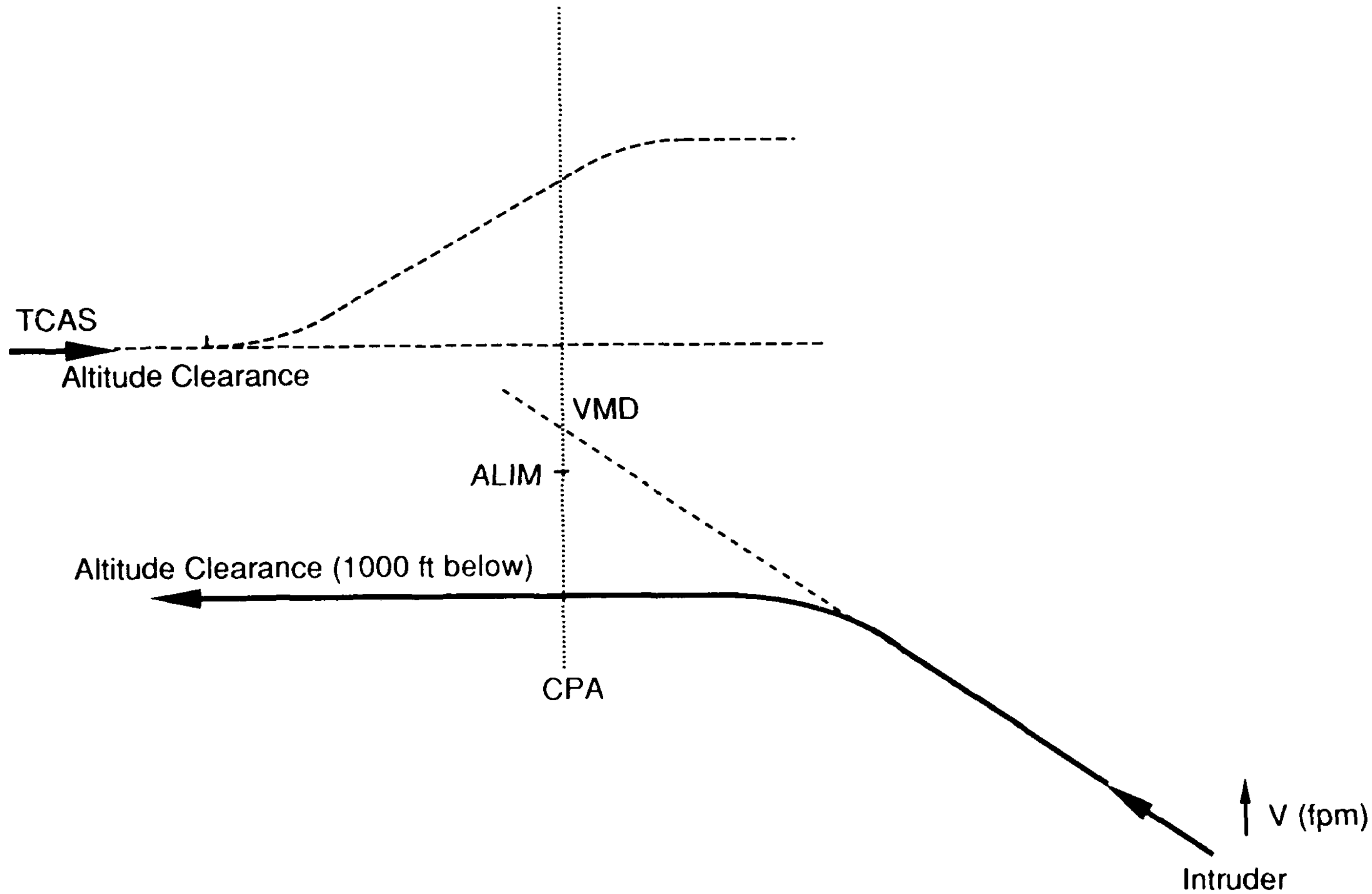


FIGURE 11
FORCED ALTITUDE DISPLACEMENT

expected results are shown in Figure 14: 97 percent of these encounters would cause the TCAS aircraft to displace less than 300 feet, 3 percent between 300 and 400 feet, and the frequency of any larger displacements is too small to be estimated.[19]

In summary, the great majority of such encounters requires little displacement by the level TCAS aircraft, so long as both aircraft seek to adhere to their IFR clearances. Any substantial overshoot or drift from cleared altitude assignments, however, would result in the posting of an RA.

[19]In Piedmont Phase II (Ref. 16), there were 2 cases of a level TCAS displacing between 300 and 400 ft, and one case of displacement between 200 and 300 ft (out of a total of 38 RAs)—a result that is in line with the above analysis.

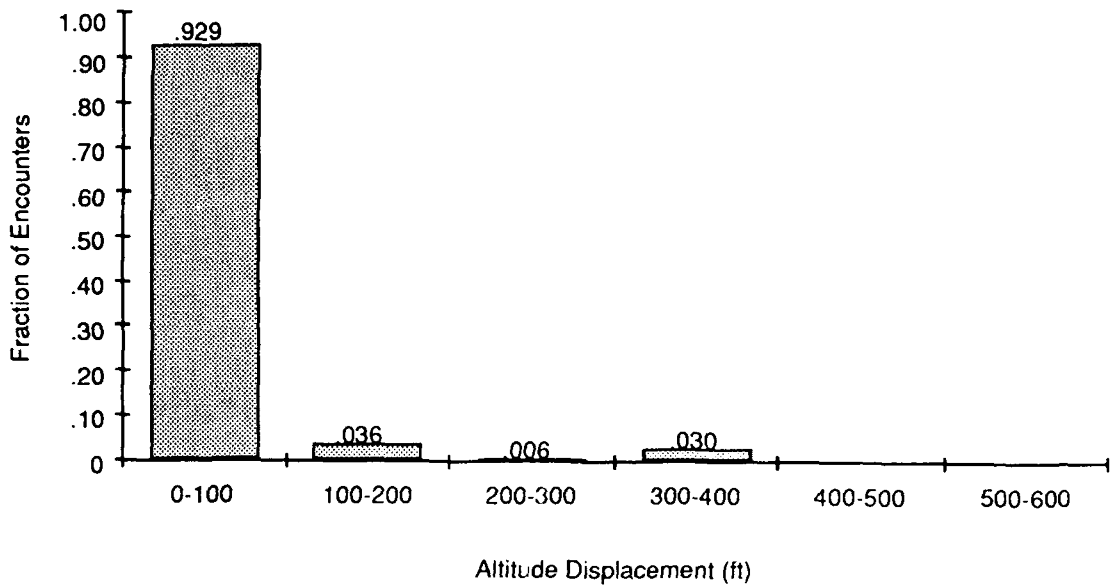


FIGURE 12
HISTOGRAM OF FORCED ALTITUDE DISPLACEMENTS

SECTION 8

CONCLUSIONS

Since the original TCAS II System Safety Study and its companion IMC study were completed, new data has become available and some new concepts have been introduced to enhance the collision avoidance logic. For instance, several measurement programs designed more clearly to describe the accuracy in reported altitude of the present Mode C system have been completed. Similarly, a substantial data base of radar-recorded data has become available to more clearly describe the maneuvers of aircraft and their proximity in the dense airspace near terminal areas. At the same time, flight experience, especially of an operational nature, has occurred. Significantly, the collision avoidance logic has been modified to bias against altitude-crossing maneuvers, and to call for either a reversal of the TCAS' vertical rate or an increase of it, if determined to be necessary. These latter considerably improve the ability of TCAS to cope with maneuvering intruders.

An overall representation comparing the impact of these effects is depicted in Figure 15. In this figure, the probability of a critical Near Midair Collision occurring today, without TCAS, is represented by the column on the left. The next column shows the Risk Ratio that was computed previously in Ref. 1. Susceptibility to maneuvering intruders was deemed to be the leading cause of induced failures, although not by a large factor. The total value for Risk Ratio is shown at the top of the column.

The third column represents the results of this study, which includes the updated information on altimetry, aircraft maneuvers, and modifications to the collision avoidance logic. The large unresolved component, being caused principally by aircraft flying without transponders and Mode C altitude encoders, remains virtually the same; the contribution of the maneuvering intruder to the induced component is somewhat reduced. The net result, however, is that the performance is very close to that which had been predicted formerly, the new factors tending to offset each other.

The fourth column represents the predicted effect of instituting the proposed rule that would require transponders and Mode C altitude reporting by all aircraft within 30 nmi of the principal airport of a Terminal Control Area or a Terminal Radar Service Area, a further improvement of about 2 to 1.

In summary, after about 5 years of additional investigation and development, the System Safety implications remain about the same. TCAS can be expected to resolve from 75 to 90 percent of the current critical near midair collisions (thereby presumably of actual midair collisions), while causing them on its own at a rate of about 1 percent (1 critical near midair collision in 10^7 flight hours or less than 1 actual midair collision in about 10^9 flight hours). For instrument weather conditions, both factors have been shown to improve somewhat, because the more organized structure and utilization of the airspace more than compensates for the assumed lack of visual acquisition.

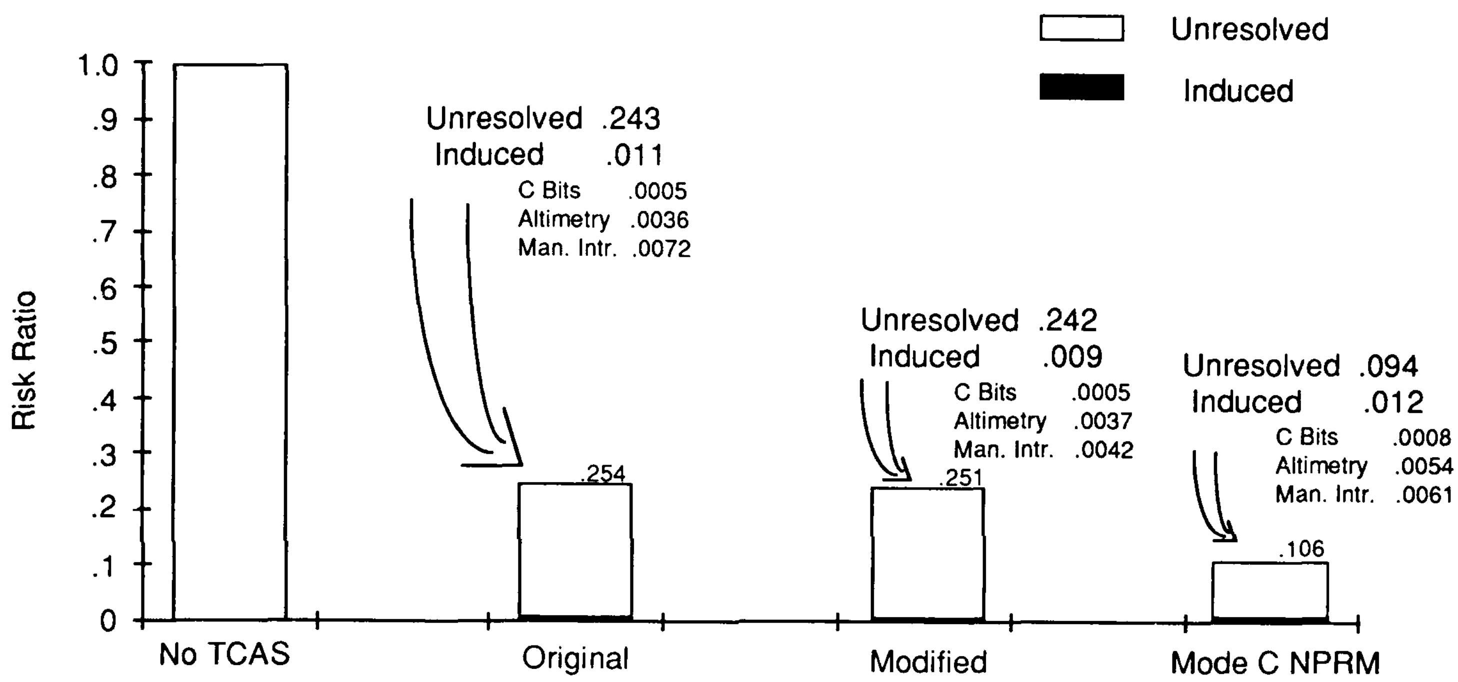


FIGURE 13
COMPARISON OF RESULTS

APPENDIX A

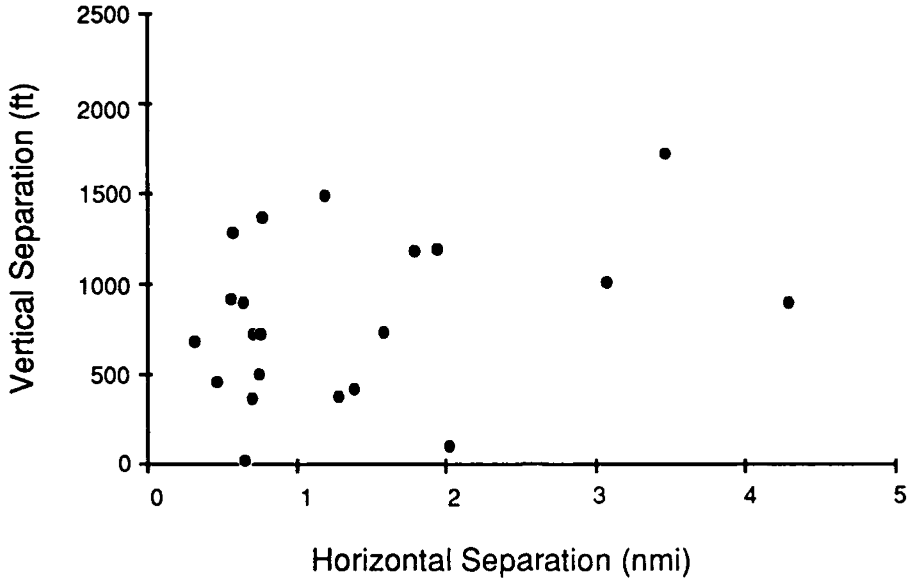
VERTICAL DISTRIBUTION

Recently, a substantial recorded data base of high density traffic within about 50 miles of a terminal radar was analyzed by the United Kingdom (Ref. 15). The extent of this data base (over 10,000 flight hours) far exceeds that of the best previously available ones (less than 2000 flight hours). Three important characteristics of the maneuvering aircraft population can be abstracted from this data: the distribution of vertical rates, the proclivity toward level-off maneuvers, and the distribution of vertical separations at CPA. The former two will be used in determining the fraction of RAs that may cause the aircraft to come within 100 ft vertical separation; the latter one, the subject of this Appendix, will be used to relate that portion of those RAs to the current NMAC rate (Risk Ratio).

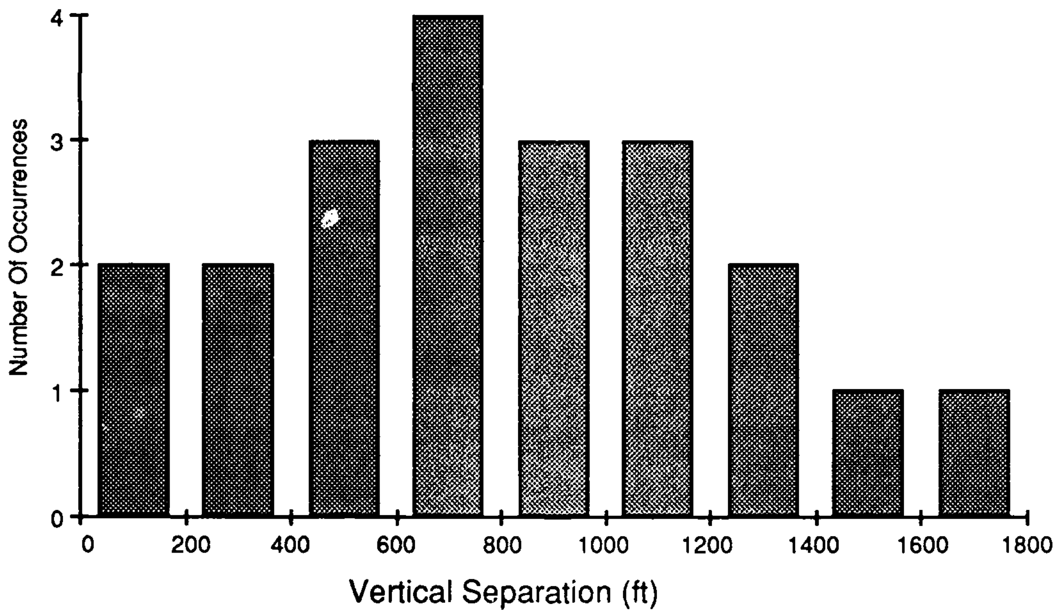
To obtain Risk Ratio, the computed fraction of all RAs that come to within 100 ft vertically is normalized to the current number of NMACs. For example, in Ref.1, this normalization process was carried out by introducing a multiplication factor of 10. This assumes a uniform distribution (out to 1000 ft) of vertical miss distance at the time of CPA, which was inferred from the Piedmont Phase I experience (see Figure 16, where both a scatter plot of the separation at CPA and the histogram of vertical miss distance lend rough justification to that inference).

Using the UK data on RAs and arbitrarily restricting all encounters to those which actually came within one nautical mile at CPA, gives the result of Figure 17. For this case, the total number of such encounters is 81; the number within 100 ft is 2. Therefore, this study will use a multiplier of 50, rather than the factor of 10 that was used formerly. This non-uniform, extended distribution applies both to altimetry errors and to the maneuvering intruder.[20]

[20]There would be little effect on the unresolved Risk Ratio—those encounters that without TCAS would come within ±100 ft vertically.



a) Scatter Chart



b) Histogram

FIGURE 14
PIEDMONT DATA DISTRIBUTIONS

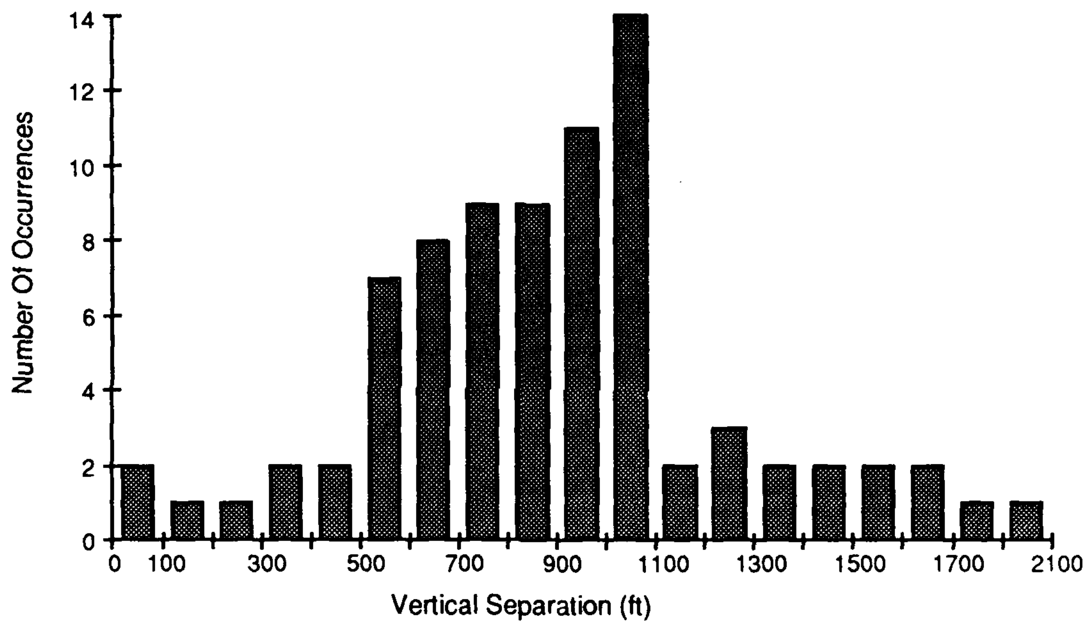


FIGURE 15
U.K. DATA DISTRIBUTIONS

APPENDIX B

MANEUVERING INTRUDER CALCULATION

The operation of the modified logic when a level TCAS aircraft encounters an intruder having a vertical rate was described in Section 4.1.2; Figure 18 shows the basis for estimating the resulting Risk Ratio. For a given projected vertical miss distance (VMD) and intruder's vertical velocity (V), the least time available for reversing (the worst level-off altitude) occurs when the intruder is just BUFF feet below the *current* altitude of the TCAS aircraft. Any later, the TCAS aircraft will proceed on down and achieve a separation of at least SNR; any earlier, the TCAS aircraft will reverse and achieve a separation of at least SR. The basis of the calculation is to assume the lesser of these two separations at this worst altitude.

Figure 19 presents the formulation, and gives an example for a 2000 fpm intruder initially projected to cross 200 ft above the TCAS altitude. From the time that the two aircraft are 100 ft apart in altitude, there are 15.62 s remaining until the CPA is reached. In this time, accounting for 2.5 s pilot delay and 1/3 g acceleration, the reversing TCAS aircraft will descend an additional 94 ft before it starts gaining altitude. It will end up with a separation of 240 ft by this process of reversing. If the intruder levelled off slightly later, the TCAS aircraft would not have reversed, continuing on to CPA with a separation of at least 290 ft.

Using the formulas of Figure 19, the combinations of initial VMD and intruder's vertical rate for which at least 100 ft of separation is obtained (no NMAC), assuming a crossing maneuver by TCAS and this worst case of level-off by the intruder, are shown in Table 3.[21] In the unshaded area, greater than 100 ft of altitude separation can be obtained (no NMAC) regardless of when or if the intruder levels off. It can be seen that the minimum achievable separation decreases as the intruder's vertical rate increases, but there are fewer encounters at very high rates. It can also be seen that the minimum achievable separation decreases as the initial VMD decreases. This is caused by the fact that a lower VMD, for the crossing encounters, is accompanied by a lesser time available for getting clear (less time to closest approach)[22] .

Table 4 shows the result of an analysis similar to that done in Ref. 1 on p. 4-38. The third column denotes those initial VMDs below which an NMAC could occur, if a crossing were made. (This can be interpolated from Table 3 or calculated directly as from Figure 19). The forth column is simply the

[21]To account for delaying issuance of an RA if the aircraft are separated by more than 900 ft, a correspondingly shorter "effective TAUV" was used in the calculations for those conditions. No mention is made of adapting TAUV to the closing velocity, known as the "Bramson Criterion," because for low vertical rates, it will give approximately the same average result, and for high vertical rates, its effect is dominated by the 900 ft condition.

[22]The calculations are deliberately pessimistic and result in simple pass/fail regions. Actually, however, simulations show substantial "pass" in the shaded region and minor "fail" in the clear region.

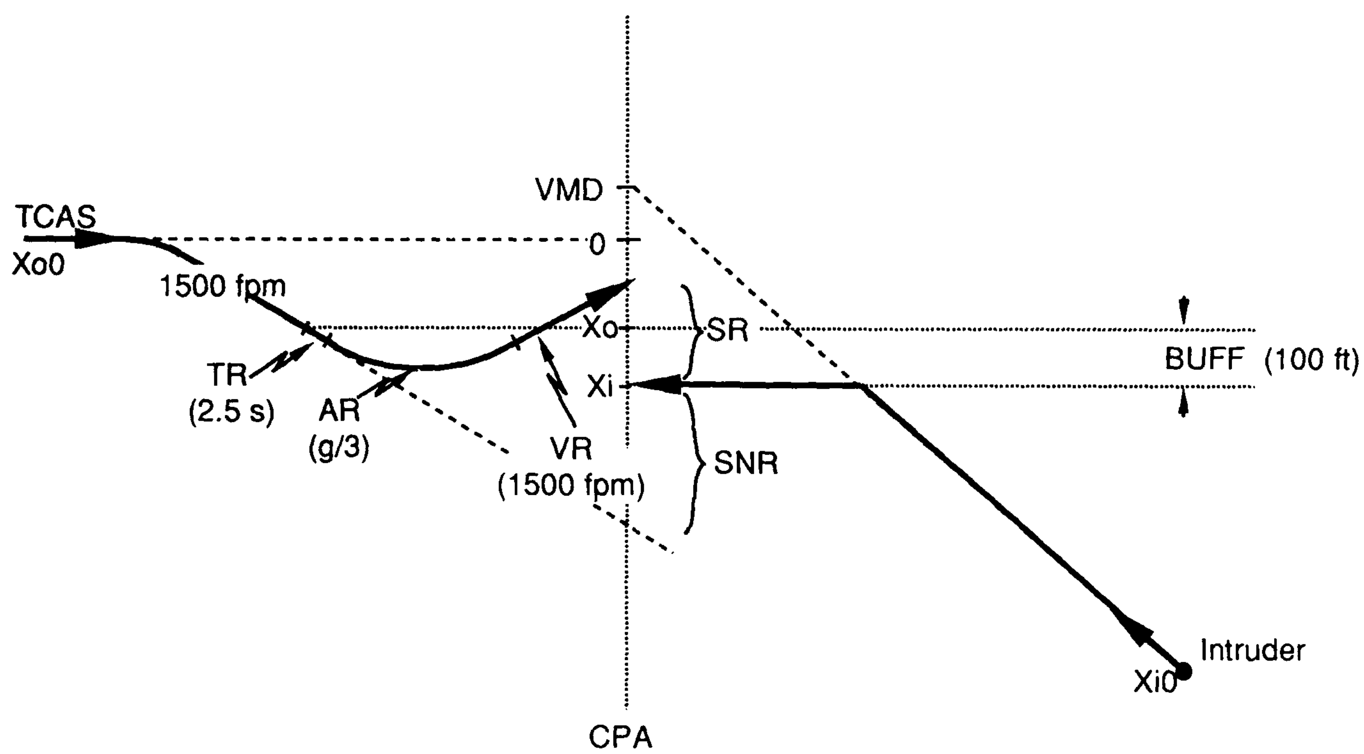


FIGURE 16
REVERSAL GEOMETRY

VMD = Initial Vertical Miss Distance
Xi0 = Initial intruder position   Xi0 = -(V/60) * TAUV
Xi = Intruder altitude at level-off   Xi = Xi0 + (V/60) * TB = (V/60) * (-TAUV + TB)
Xo0 = Own initial position = 0 ft
Xo = Own altitude at time of level-off   Xo = Xacc - 25 * (TB - 8.125)   Xacc = -39.063 ft (During first acceleration)

TAUV = Time from start to coaltitude
TB = Time for intruder to get to Xi = Time for own to get to Xo.   Xo - Xi = BUFF
TB = ((V/60) * TAUV + 164.062 - BUFF) / ((V/60) + 25)

TMIN = Min. time available for reversal = Time to CPA - TB
TMIN = (TAUV + (60 * VMD/V)) - TB

TLVL = Time to level off after decision to reverse
TLVL = TR + 25/AR;   TR = 2.5 s, AR = 10 fps (1/3 g)

TACC = Available time to accelerate after TCAS levels off = TMIN - TLVL
TAMX = Max. time needed to accelerate from level to 1500 fpm = VR / (60 * AR)

OSHT = Overshoot from time reversal is posted until TCAS levels off = -(25*TR) - (312.5/AR)

YACC = Distance covered in accelerating from level
YACC = IF(TACC > TAMX, (AR/2)*TAMX^2, (AR/2)*TACC^2)

TLIN = Time available for linear rate after acceleration
TLIN = IF(TACC > TAMX, (TMIN-TLVL-TAMX), 0)
YLIN = Distance covered with linear rate = (VR/60) * TLIN

SR = Separation with a reversal = OSHT + YACC + YLIN + BUFF
SNR = Separation with level-off and no reversal = (25 * TMIN) - BUFF
S = MIN(SR : SNR)

TAUV	25 sec
V	2000 fpm
VMD	200 ft
BUFF	100 ft
VR	1500 fpm
TR	2.50 s
AR	10 fpsps
TLVL	5.00 s
TB	15.38 s
TMIN	15.62 s
TACC	10.62 s
TAMX	2.50 s
OSHT	-93.75 ft
YACC	31.25 ft
TLIN	8.12 s
YLIN	202.90 ft
SR	240.40 ft
SNR	290.40 ft
S	240.40 ft

FIGURE 17
WORST CASE FOR CROSSING LEVEL-OFFS

TABLE 3
MINIMUM SEPARATIONS

Intruder's Vertical Rate (fpm)

Initial Vertical Miss Distance (ft)	1000	2000	3000	4000	5000	6000
0	187	90	6	-25	-52	-68
50	262	128	13	-7	-37	-55
100	337	165	29	8	-22	-43
150	412	203	54	7	-7	-30
200	487	240	79	11	8	-18
250	562	278	104	21	6	-5
300	637	315	129	37	8	7
350	712	353	154	56	12	6
400	787	390	179	75	21	7

Region Of Possible NMAC

TABLE 4
MANEUVERING INTRUDER CALCULATION

1	2	3	4	5	6	7	8	9	10	11
V	Freq	VMD (ft)	Potential	Time to 900 ft	Time below window (s)	Total Time Below (s)	Pr (No Acc.)	Time in window (s)	Pr (Acc.)	Pr (<100 ft)
3840	0.002	400	0.500	11	11	22	0.454	2.25	0.078	0.000035
3600	0.000	380	0.475	10	11	21	0.470	2.35	0.081	0.000000
3360	0.002	325	0.406	9	12	21	0.471	2.47	0.085	0.000033
3120	0.004	270	0.338	8	13	21	0.475	2.60	0.089	0.000057
2880	0.004	215	0.269	6	13	19	0.500	2.74	0.094	0.000050
2640	0.008	155	0.194	5	15	20	0.495	2.90	0.099	0.000076
2400	0.008	93	0.116	3	15	18	0.533	3.08	0.105	0.000052
2160	0.008	30	0.038	0	16	16	0.562	3.28	0.111	0.000019
1920	0.006	5								
1680	0.022	0								
1440	0.018	0								
1200	0.028	0								
960	0.060	0								
720	0.100	0								
480	0.122	0								
	1.000									0.00032

ratio of that VMD to 800 ft, the total range of VMDs for which corrective RAs are given (thereby sending the TCAS aircraft off on its original descent). Column 5 shows the time that the modified logic delays, waiting for the intruder to cross through the 900 ft threshold, expecting an ATC level-off action to occur; column 6 is the time remaining after crossing that threshold until the two aircraft are within 100 ft of each other's altitude; column 7 is their sum—a relatively constant time during which an intruder's level-off would avoid an NMAC.

The probability of a level-off occurring is given in column 8. Ref. 1 found that the probability of an intruder levelling off within a stated time interval was well approximated by the following formula:

$$Pr = 1 - \exp(-.036 \times T) \qquad (1)$$

Where Pr is the probability of an acceleration (e.g. a level-off) occurring in the next T seconds.

A similar estimate is given in the following two columns for the time during which the ascending intruder is within the critical window. All of this enables estimating the probabilities, similar to Ref. 1, of the intruder maneuvering at just the right time to cause an NMAC. The product of columns 2, 4, 8, and 10 is the probability that, because of the intruder's maneuver, TCAS would cause the aircraft altitudes to come within 100 ft for each of the vertical rates encountered.[23] The result of this is that, because of an intruder suddenly levelling off, TCAS could cause the two aircraft to come within 100 ft of each other in 3.2×10^{-4} of all RAs; this is to be compared with 2.7×10^{-3} (.0027), as determined in Ref. 1 with the current logic (nearly an order of magnitude improvement when compared on the same basis).

[23]This simplified estimate does not account for those cases of projected crossing encounters that would be converted to non-crossings because ALIM separation could be achieved.

APPENDIX C

MANEUVERING INTRUDER CALCULATION: UK-SUPPLIED DATA

Because of the availability of the large data base analyzed by the UK, it is instructive to use that to calculate the induced Risk Ratio caused by maneuvering intruders. Since the data base was large enough to contain many RAs, the technique previously used of examining the vertical-rate characteristics of TAs together with RAs to increase the size of the data base is not necessary, but a consistent approach must be developed to use this new data for calculating the effects of maneuvering intruders.

The two important characteristics for calculating these effects are the vertical rates that the TCAS aircraft is likely to encounter when it must choose its own RA, and the expectation that the intruder will suddenly change his vertical rate shortly after that choice is made. The previous work, as described in Ref. 1, joins in one data base all intruders that would have created either a TA or an RA. One consequence is that there may be a lower fraction of high vertical rates than if only the RAs were used. A second consequence is that the probability of an intruder's levelling off is descriptive of that merged population (this was the Poisson distribution noted in Ref. 1 and also used in this report).

Figure 20 shows the distribution of vertical rates both from the merged data (TA plus RA) of the Piedmont Phase I flights[24] and from the RA-only data as used by the UK. It can be seen that there is a larger fraction of high-rate encounters in the ground-based data. To use this data set, however, it is necessary to evaluate anew the probability of a vertical acceleration as a function of time. Fortunately, the UK analysis was first conducted using the standard parameters (e.g., 25 seconds for TAUV). It was then possible to inspect graphical data and obtain a measure of the equivalent "instant" after an RA that a vertical acceleration was made.[25] The result is shown in Figure 21, where it can be seen that a large fraction of level-offs do occur within about 15 seconds after an RA. However, it can also be seen that if this acceleration did not occur within about 15 seconds, it was unlikely to occur at all.

The calculations shown in Table 5 are similar to those previously shown in Table 4, except that the vertical rate distribution and the probability of a vertical acceleration are both taken from the UK data, as depicted in Figures 20 and 21. As before, the issuance of the RA is delayed until the current vertical separation is less than 900 ft. The similarity of results of the two sets of data is encouraging.

[24] As noted earlier, the data obtained from Phase II of the Piedmont flights was quite similar to that of Phase I.

[25] This was determined from the intersection of the "before" and "after" asymptotes of vertical rates on plots of data.

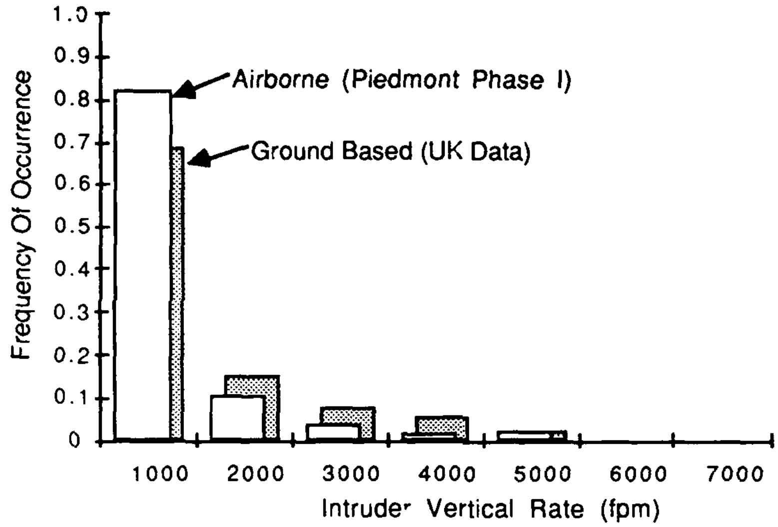


FIGURE 18
COMPARISON OF VERTICAL RATES

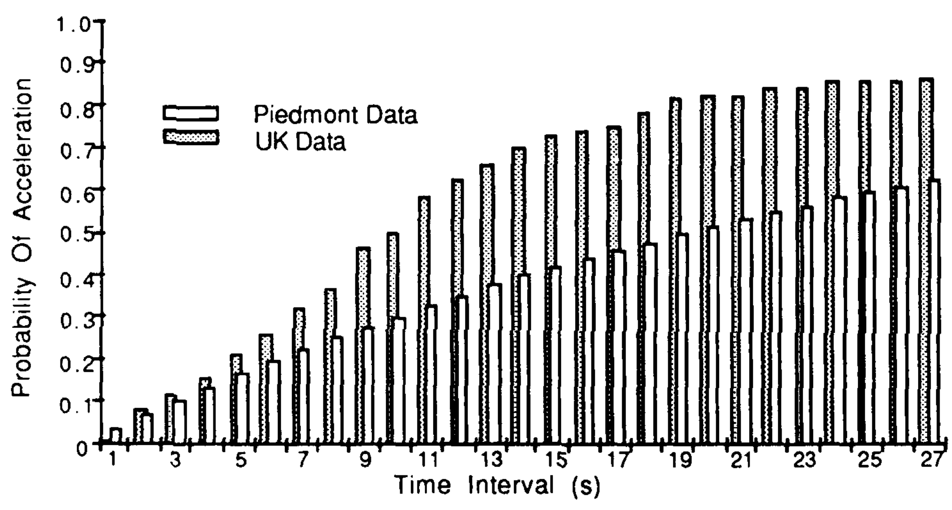


FIGURE 19
COMPARISON OF PROBABILITY OF VERTICAL ACCELERATION

TABLE 5
MANEUVERING INTRUDER CALCULATION: UK DATA

1	2	3	4	5	6	7	8	9	10	11
V	Freq	VMD (ft)	Potential	Time to 900 ft	Time below window (s)	Total Time Below (s)	Pr (No Acc.)	Time in window (s)	Pr (Acc.)	Pr (<100 ft)
7000	0.003	400	0.500	17	7	24	0.148	1	0.016	0.000003
6600	0.000	400	0.500	17	7	24	0.148	1	0.016	0.000000
6200	0.000	400	0.500	16	7	23	0.164	2	0.016	0.000000
5800	0.000	400	0.500	16	8	24	0.148	2	0.016	0.000000
5400	0.000	400	0.500	15	8	23	0.164	2	0.016	0.000000
5000	0.003	400	0.500	14	9	23	0.164	2	0.016	0.000004
4600	0.008	400	0.500	13	9	22	0.164	2	0.016	0.000011
4200	0.014	400	0.500	12	10	22	0.164	2	0.016	0.000019
3800	0.023	400	0.500	11	11	22	0.164	2	0.016	0.000030
3400	0.034	335	0.419	9	12	21	0.180	2	0.009	0.000023
3000	0.025	244	0.305	7	13	20	0.180	3	0.074	0.000103
2600	0.045	145	0.181	4	14	18	0.221	3	0.058	0.000105
2200	0.011	40	0.050	0	16	16	0.262	3	0.082	0.000012
1800	0.062	0								
1400	0.088	0								
1000	0.121	0								
600	0.220	0								
200	0.342	0								
	1.000									0.00031

APPENDIX D

FREQUENCY OF REVERSALS

For the modified logic, it is instructive to estimate the probability that an RA issued against a non-TCAS aircraft will ultimately be reversed because of that intruder's sudden maneuver. The process is similar to that of the maneuvering intruder calculation of Appendix B.[26] A reversal will be issued if (1) an initial crossing RA would have been generated, (2) the intruder does not level off before reaching 900 ft, and (3) he does level off by the time he reaches 100 ft of the TCAS altitude. Table 6 gives these values, resulting in an estimate that 6/10 of one percent of all RAs will transition to reversals.

[26]For a level TCAS aircraft, an initial crossing RA can be issued only if ALIM clearance cannot be achieved in the non-crossing sense, and if the aircraft are initially between 300 and 900 ft apart.

TABLE 6
FREQUENCY OF REVERSALS

V	Freq	Fraction Crossing Positives	Time to 900 ft	Time below window (s)	Pr Reversal
3840	0.002	0.193	11	11	0.0001
3600	0.000	0.193	10	11	0.0000
3360	0.002	0.193	9	12	0.0001
3120	0.004	0.193	8	13	0.0002
2880	0.004	0.193	6	13	0.0002
2640	0.008	0.193	5	14	0.0005
2400	0.008	0.193	3	15	0.0006
2160	0.008	0.193	0	16	0.0007
1920	0.006	0.193	0	15	0.0005
1680	0.022	0.193	0	14	0.0017
1440	0.018	0.127	0	14	0.0009
1200	0.028	0.060	0	13	0.0006
960	0.060	0.000	0	11	0.0000
720	0.100	0.000	0	10	0.0000
480	0.122	0.000	0	8	0.0000
					0.0061

APPENDIX E

DISPLACEMENT FROM AN ALTITUDE CLEARANCE

For the current logic, displacement of a level TCAS aircraft from its altitude clearance caused by a transitioning aircraft arriving at its own altitude clearance 1000 feet away is illustrated in Figure 22. The result will depend on the intruder's initial vertical rate (V) and projected vertical miss distance (VMD), both of which also determine the initial vertical separation, S.

The following parameters are defined:

TAUV[27]	Time to coaltitude. Total time available for resolution (s)
VMD	Projected separation at CPA (ft)
D	Total displacement (ft)
Da	Displacement during acceleration phase (ft)
Do	Overshoot displacement (assume 100 ft)
Dv	Displacement at constant rate of 1500 fpm (ft)
S	Initial separation (ft)
T	Time during which TCAS "believes" it is threatened, after which it sees the level-off (s)
V	Intruder's vertical rate (fpm)
Y	Clearance separation (assume 1000 ft)

The time by which the intruder levels off, and the initial separation are, respectively,

$$T = TAUV - (60 \times Y/V) \tag{1}$$

$$S = TAUV \times V/60 \tag{2}$$

If the geometry is such that a corrective RA is generated, it will last until the TCAS aircraft's altitude is (ALIM + 75) ft above the intruder's expected altitude at CPA, or until the intruder's level-off is detected. Then the TCAS aircraft will be able to return to its clearance, but will overshoot by approximately 100 ft in so doing.

To determine the total displacement, the total time available is computed, conservatively assuming the intruder to make an instantaneous level-off.[28] If this time is not greater than the 5 seconds assumed for pilot delay, there will be no displacement; otherwise there will be some displacement in reacting to

---

[27]TAUV and VMD are parameters in the collision avoidance logic.

[28]A relatively abrupt level-off is necessary to force any TCAS displacement. A gradual transition, such as described in the Airman's Information Manual (Ref. 14), would rarely result in a corrective RA.

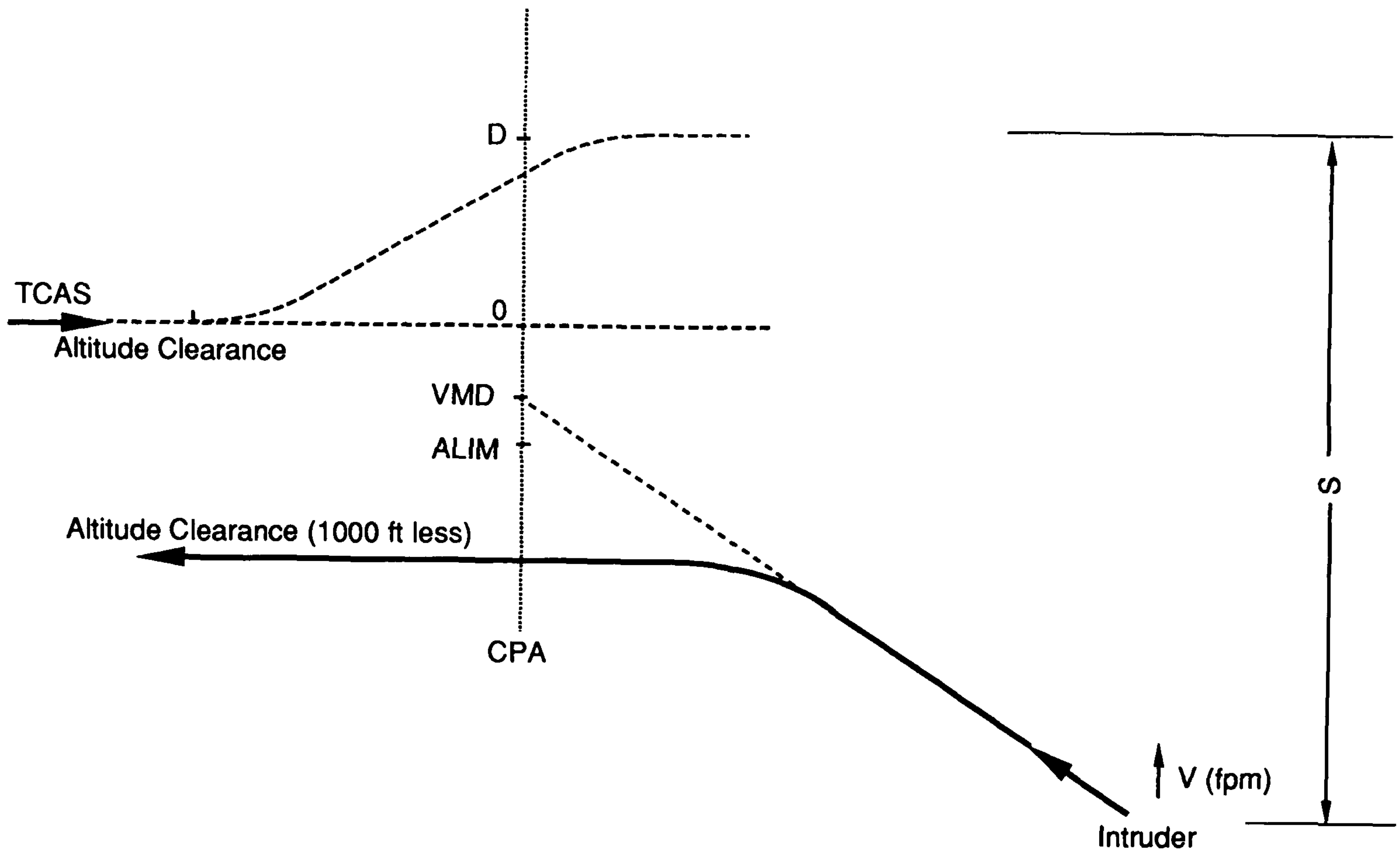


FIGURE 20
FORCED ALTITUDE DISPLACEMENT

the RA, plus the assumed 100 ft (a simplification of real overshoot). If the available time permits,[29] the TCAS aircraft will accelerate to 1500 fpm, and the remainder of the displacement will be achieved at that rate; if not, the lesser amount of displacement is estimated.

Table 7 shows the calculated displacements for Sensitivity Level 6, Altitude Layer 3 (18,000 - 30,000 ft). The Table is shown partitioned into regions of 100 ft displacement intervals. The frequency of occurrence of each cell in the matrix is obtained from the experience of the Piedmont Phase I flights; the vertical rates were measured as shown across the bottom of Table 8 and the vertical miss distance was determined to be relatively uniformly distributed. This enabled the entire frequency-of-occurrence matrix to be filled out as shown. The frequencies of Table 8 were multiplied by the displacements of Table 7 to get the histogram of displacements shown in Figure 14 of the main text.

[29] At 1/4 g, it takes 3.125 seconds to accelerate from 0 to 1500 fpm.

TABLE 7
DISPLACEMENT MATRIX

Intruder's Range of Vertical Rates (fpm)

Vertical Miss Distance (ft)	0-1,000	1,000-2,000	2,000-3,000	3,000-4,000	4,000-5,000	5,000-6,000
-100	0	0	186	311	386	436
-200	0	0	186	311	386	436
-300	0	0	186	311	386	436
-400	0	0	186	311	386	415
-500	0	0	186	311	315	315
-600	0	0	186	215	215	215

TABLE 8
FREQUENCY OF OCCURRENCE MATRIX

Intruder's Range of Vertical Rates (fpm)

Vertical Miss Distance (ft)	0-1,000	1,000-2,000	2,000-3,000	3,000-4,000	4,000-5,000	5,000-6,000	
-100	0.137	0.018	0.006	0.002	0.004	0.000	0.167
-200	0.137	0.018	0.006	0.002	0.004	0.000	0.167
-300	0.137	0.018	0.006	0.002	0.004	0.000	0.167
-400	0.137	0.018	0.006	0.002	0.004	0.000	0.167
-500	0.137	0.018	0.006	0.002	0.004	0.000	0.167
-600	0.137	0.018	0.006	0.002	0.004	0.000	0.167
	0.822	0.108	0.036	0.012	0.024	0.000	1.00

APPENDIX F

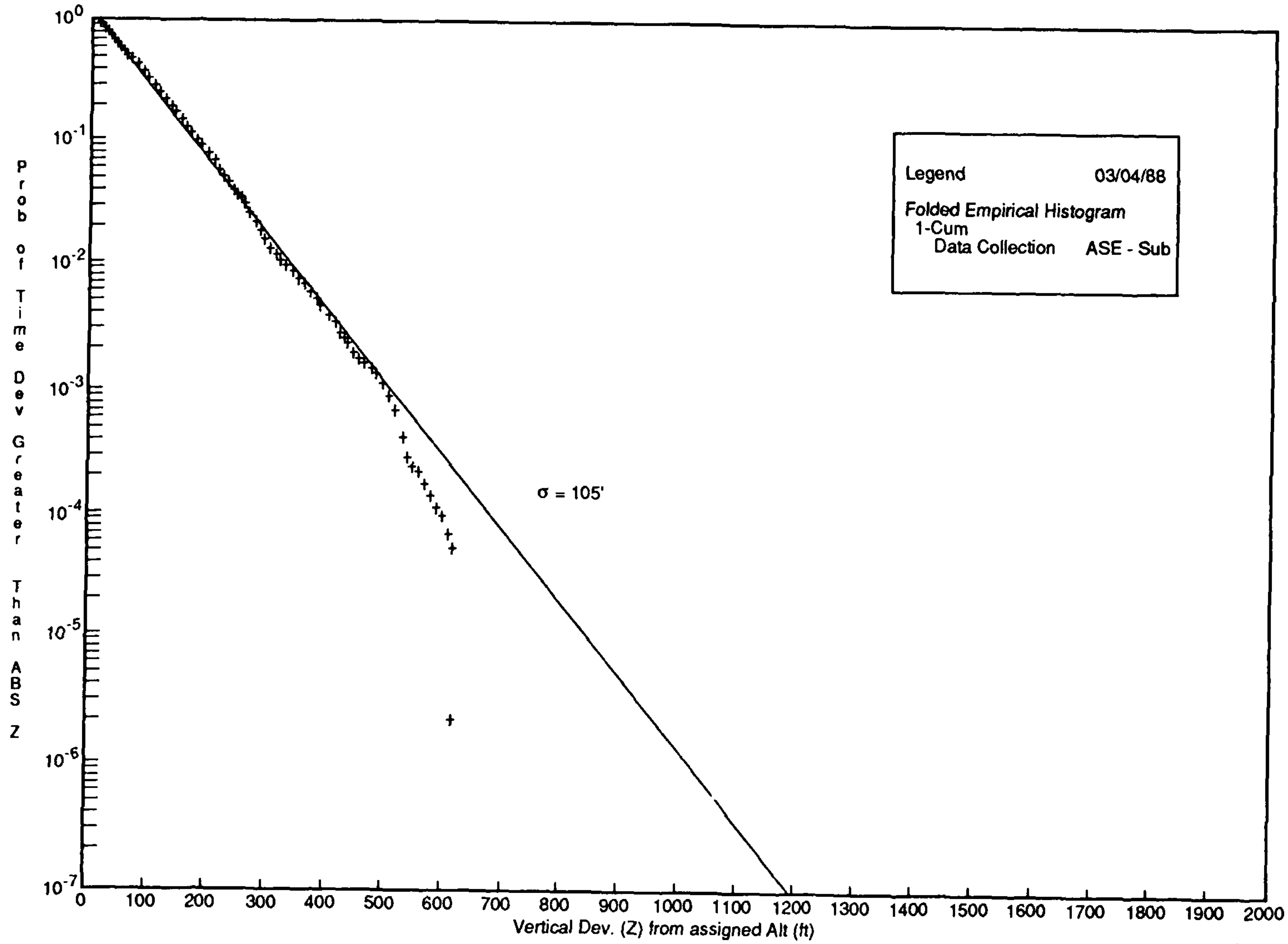
ALTIMETRY DATA AT HIGH ALTITUDES

In 1986, the FAA Technical Center observed over twelve hundred aircraft at high altitude (above Flight Level 290) in the vicinity of Nashville, Tennessee; Figure 23 is a summary of that data. As shown, the plotted data is well represented by a straight line that intercepts the 10^{-7} probability at an error of 1200 ft. This can be interpreted as a "double exponential" (symmetrical exponential) distribution with a standard deviation of 105 ft.[30] This is replotted in Figure 24 as the dotted line. Also shown in Figure 24 is the Gaussian distribution used in the former calculations of Ref. 1, having a standard deviation of 192 ft for a general aviation intruder.

In the previous work, only 79 percent of the aircraft were assumed to be characterized by the distribution of Figure 24. Now, however, the data described by the FAA Technical Center is for all aircraft. So if one were to consider only the high altitude airspace, in which the altitude error of all other aircraft is described by the double exponential distribution with a standard deviation of 105 ft, and if the vertical separation normally encountered at CPA were that of Figure 17, the risk ratios would work out to be .0112 for the induced component and .0014 for the unresolved component, giving .0126 total. This is 60 percent of that obtained using the former data. Additionally, these basic values for Risk Ratio would subsequently be reduced to account for improved visual acquisition as aided by the Traffic Advisory display.

30

$$\sigma = \frac{-\sqrt{2}\,x}{\ln(\text{Probability})}$$



From Ref. 5

FIGURE 21
ONE MINUS THE CUMULATIVE RELATIVE FREQUENCIES FOR ALTIMETRY SYSTEM ERROR ABSOLUTE VALUES

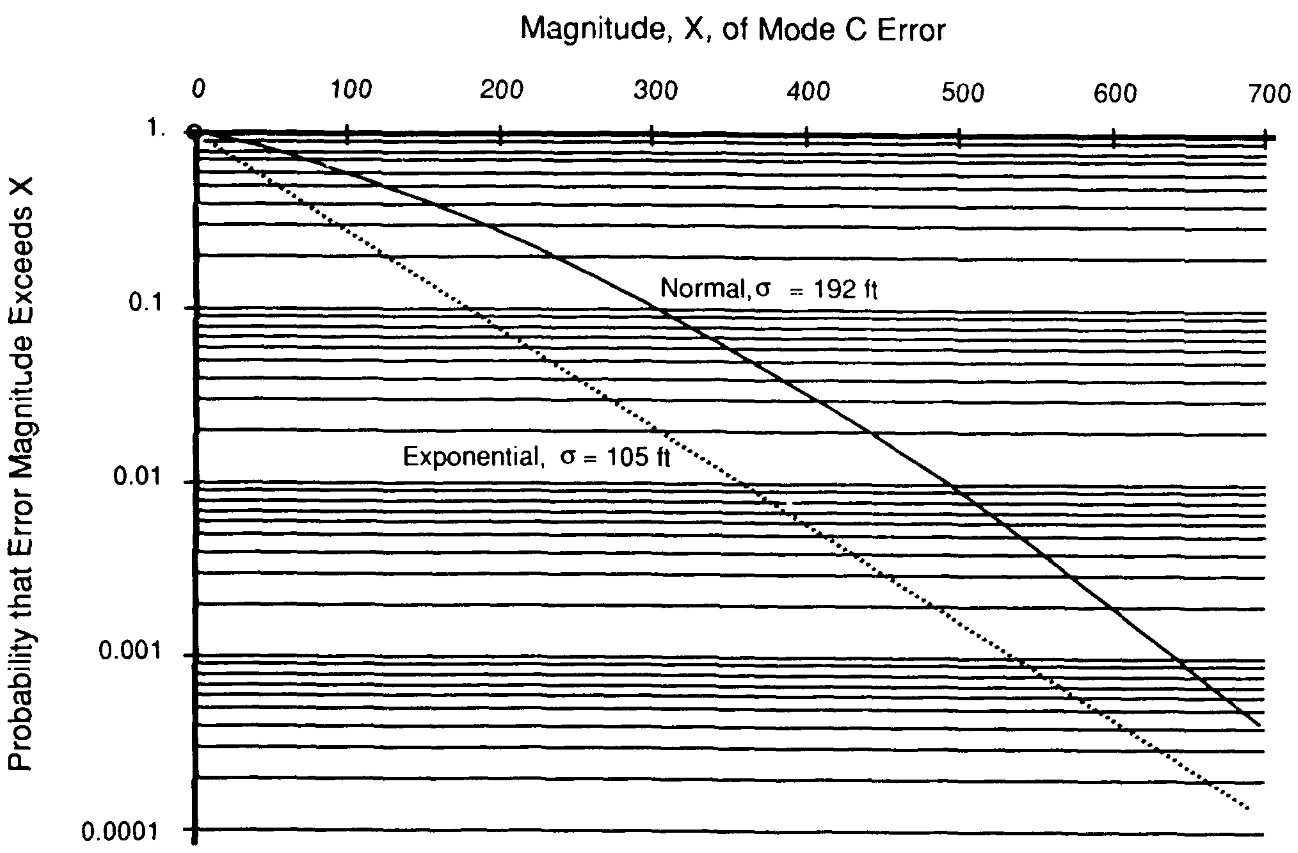


FIGURE 22
MODE C ERROR DISTRIBUTION AT HIGH ALTITUDES

APPENDIX G

EQUIPMENT FAILURES

The TCAS equipment complex includes the displays, the Mode S transponder, various input sensors (such as altimeters), and the units proper to the TCAS itself. Equipment failures could possibly cause the generation of a wrong-sense advisory, and could also cause the coordination mechanism to fail.

WRONG SENSE ADVISORY

It can be postulated that the most serious mode of equipment failure is a sense reversal—in which an undetected equipment failure causes the wrong sense to be generated, thereby directing the TCAS aircraft into rather than away from the other aircraft. This "ultimate failure" would admittedly be quite difficult to remain undetected in normal digital equipment. A failure in memory cells or in control gates would almost inevitably be sensed in the normal performance monitoring function built into the system, as these effects can be expected to affect many functions.

In an attempt to place some basic requirements on the performance monitoring system, one can estimate the probability of an NMAC without performance monitoring, account for the reduction of that probability for an actual midair collision (usually agreed to be a factor of 1/10 to 1/100), and then determine the requirement on performance monitoring to reduce the probability to a tolerable level. This is the approach typically used by the FAA certification authorities (Ref. 8); a final probability of 10^{-9}, being well below the most stringent goals.

For such an equipment failure to lead to an NMAC, there must first be a corrective RA, which occurs with a frequency of 1 in 40-80 hours. Second, visual acquisition must not be effective; Ref. 1 showed that to occur with about 20 percent probability. Finally, the two aircraft must be close horizontally, and they must end up within 100 ft vertically (an NMAC). It should be realized that, if the distribution of vertical separation at CPA were uniform, the probability of the intruder being at that worst-case altitude would be exactly two times that of his being coaltitude at some other time. That is to say, while coaltitude NMAC encounters would be resolved (even a reverse sense motion would be effective), there are two equivalent regions of airspace, one above TCAS and one below it, that would now become the hazardous zones. Thus, the probability of an NMAC with this equipment failure would be twice that for an NMAC without TCAS at all. From the data of Figure 17 however, one can infer that, while the distribution is not uniform, the factor of increase would be less than 10.

Therefore, the probability of an undetected equipment failure introducing a reversed sense RA that leads to a midair collision can be estimated as follows:

	P(a corrective RA is generated)	1/40 per flight hour
x	P(no visual acquisition possible)	.2
x1	P(NMAC without TCAS)	10^{-5}
x 2 x 10		20
x	P(NMAC will become MAC)	<u>1/10</u>
	Product	1×10^{-7}

Thus, the requirement for an effective performance monitoring system is on the order of 10^{-2}, a modest requirement for high quality avionics systems; an achievable undetected failure rate of greater than 10^{-3} to 10^{-4} appears to be a reasonable practical requirement, and one that gives a large margin of system safety. In addition, pilot checks performed with the usual ground checklist procedures, and observation of the normally encountered RAs both establish some further level of backup to catch any failure of this sort.

COORDINATION FAILURES

In Ref. 12, M.I.T. Lincoln Laboratory has estimated the effects of a short-term failure of the transmission path between two coordinating TCAS aircraft. The probability of such a failure causing a midair collision because coordination could not be effectively established was found to be extremely low and tolerable. The question remains, "What is the effect of a hardware failure at the time of such coordination?"

If the failure were to occur prior to the second aircraft declaring a threat, there would be a no competing RAs; if the failure were to occur after coordination is effected, the RAs would be complimentary. Thus, the susceptible time for such a failure to occur would be during the intervening interval, which could range from several milliseconds to a maximum of about two seconds. For example, the failure of one of the TCAS transmitters during a 2-second interval when it might be needed for coordination would be expected to occur with a probability[31] of $2/(2500 \times 3600) = 2.2 \times 10^{-7}$. While this event would

[31] Typical mean time between failures of high quality avionics is about 2500 hours.

rather quickly be detected on the aircraft where the failure occurs, the information is likely not to be transferred effectively to the other aircraft, so no benefit for self-detection is claimed. Using this together with the other factors developed in Ref. 12,

	P(an RA is generated)	0.05 per flt hour
x	P(TCAS-TCAS encounter)	0.5
x	P(geometry is such that, without coordination both A/C would select the same sense)	0.2
x	P(2-second hardware failure)	2.2×10^{-7}
x	P(inadequate horizontal separation)	0.013
x	P(inadequate vertical separation)	0.038
x	P(no visual separation possible)	0.200
	Product	1.1×10^{-13}

This very low probability of an equipment failure causing a coordination failure that leads to a midair collision is well within tolerance.

APPENDIX H

EVALUATION OF FAULT TREE

The original System Safety Study for TCAS laid out an approach for combining into one integrated result the many contributing factors that might lead to an NMAC in spite of an aircraft having TCAS. Those results principally appeared in Ref. 1 on p. 7-33 and p. 7-44 for the overall unresolved and induced Risk Ratios, respectively. The same approach, but with a different representation is given in the following Figures—Figures 25 and 26 are for the original data and logic;[32] Figures 27 and 28 are for the new data discussed in this report and for the modified collision avoidance logic; Figures 29 and 30 make the further assumption that the transponder and Mode C equipage will be as envisioned with the Mode C rule fully effective.

In these Figures, indentation is used to indicate the logical steps in computing failure mechanisms; a brief explanation accompanies each input. The resulting products are formed at each step before introducing the next modification factor. Each indentation level sums to unity for its section. For example, in Figure 25, the fraction of aircraft that are Mode C equipped is .6072;[33] .3128 have no Mode C; .0800 have no transponders. Wherever there is a condition that TCAS would not be effective, a box is drawn around the product factor; all these product factors are summed and printed in bold at the bottom of the chart. It is realized that these charts may be hard to follow with this very brief explanation; they are included here for the record.

[32]This differs from Baseline assumption in Ref. 1 in that tracking of non Mode C transponder aircraft is included.

[33]Throughout this report, an excess of significant digits is used in the calculations. They will be rounded off at the end.

Unresolved RR, Non Mode C Tracking

.6072 Mode C Equipped aircraft (.92 Transponders * .66 Mode C)

.9400 TA Received

.7000 Bright Daylight

.6500 Vis. Acquired by time of RA

.2597

.3500 Not Vis. Acquired by time of RA

.9887 Adequate RA

.1383

.0113 Inadequate RA (.0143 RR * .79 GA ratio)

.5100 Vis. Acq. by 15s before CPA

.0008

.4900 No Vis. Acq. by 15s before CPA (.17/.35=.49)

.3000 All Other

.0008

.9887 Adequate RA

.1693

.0113 Inadequate RA (.0143 RR * .79 GA ratio)

.0019

.0600 No TA

.9700 RA Received

.9887 Adequate RA

.0349

.0113 Inadequate RA (.0143 RR * .79 GA ratio)

.0004

.0300 RA Not Received

.0182 (Mode C * No RA; No TA is not an independent f actor)

.3128 Non Mode C (.92 Transponders * (1-.66) Non Mode C)

0.94 TA Received

.7000 Bright Daylight

.8300 Vis. Acq. by 15s before CPA

.1708

.1700 No Vis. Acq. by 15s before CPA

.0350

.3000 All Other

.0882

Failure Sum= **.2433**

.0600 No TA

.0188

.0800 No Transponders

FIGURE 23
UNRESOLVED RISK RATIO (ORIGINAL STUDY)

Induced RR (Original Logic, Non Mode C Tracking)

Errors	Altimetry	.0137	(.0174 * .79)
	C Bits	.0020	
	Man. Intruder	.0270	
		.0427	

Fraction of Mode C = .6100

.0261 Fraction of encounters for which incorrect RA is received

.9700 TA received (given RA received)

.7000 Bright Daylignt

.8300 Vis. Acq. by 15s before CPA

.0147

.1700 No Vis. Acq. by 15s before CPA

$\boxed{.0030}$

.3000 All Other

$\boxed{.0076}$

.0300 No TA received (given RA received)

$\boxed{.0008}$

Failure Sum= .0114

Summary	.0427/.0114
Altimetry	.0037
C Bits	.0005
Man. Intruder	.0072
	.0114

FIGURE 24
INDUCED RISK RATIO (ORIGINAL STUDY)

Unresolved RR (New Logic)

.6072 Mode C Equipped aircraft (.92 Transponders * .66 also having Mode C)
    .9400 TA Received
        .7000 Bright Daylight
            .6500 Vis. Acquired by time of RA

            .2597

            .3500 Not Vis. Acquired by time of RA
                .9937 Adequate RA

                .1390

                .0063 Inadequate RA (.0080 RR * .79 GA ratio)
                    .5100 Vis. Acq. by 15s before CPA

                    .0004

                    .4900 No Vis. Acq. by 15s before CPA (.17/.35=.49)

                    $\boxed{.0004}$

        .3000 All Other
            .9937 Adequate RA

            .1702

            .0063 Inadequate RA (.0080 RR * .79 GA ratio)

            $\boxed{.0011}$

    .0600 No TA
        .9700 RA Received
            .9937 Adequate RA

            .0351

            .0063 Inadequate RA (.0080 RR * .79 GA ratio)

            $\boxed{.0002}$

        .0300 RA Not Received

        $\boxed{.0182}$ (Mode C * No RA, No TA is not an independent factor)

.3128 Non Mode C (.92 Transponders * (1-.66) Non Mode C)
    0.94 TA Received
        .7000 Bright Daylight
            .8300 Vis. Acq. by 15s before CPA

            .1708

            .1700 No Vis. Acq. by 15s before CPA

            $\boxed{.0350}$

Failure Sum= .2419

        .3000 All Other

        $\boxed{.0882}$

    .0600 No TA

    $\boxed{.0188}$

$\boxed{.0800}$ No Transponders

FIGURE 25
UNRESOLVED RISK RATIO (UPDATED)

Induced RR for New Logic

					Note
Errors	GA Altimetry	.0178	Altimetry	.0141	.0178=.0147*.86 + .0370*.14
			C Bits	.0020	
			Man. Int.	.0160	.00032*50=.0160
				.0321	(50 instead of 10)

Fraction of Mode C = .6072 (.92 Transponders * .66 also having Mode C)

.0195 Fraction of encounters for which incorrect RA is receivec

.9700 TA received (given RA received)

.7000 Bright Daylignt

.8300 Vis. Acq. by 15s before CPA

.0110

.1700 No Vis. Acq. by 15s before CPA

$\boxed{.0022}$

.3000 All Other

$\boxed{.0057}$

.0300 No TA received (given RA received)

$\boxed{.0006}$

Failure Sum= .0085

Summary	.0085/.0321
Altimetry	.0037
C Bits	.0005
Man. Int.	.0042
	.0085

FIGURE 26

INDUCED RISK RATIO (UPDATED)

Unresolved RR (New Logic, Mode C NPRM)

.8800 Mode C Equipped aircraft (.98 Transponders * .898 also having Mode C)
- .9400 TA Received
  - .7000 Bright Daylight
    - .6500 Vis. Acquired by time of RA
      - .3764
    - .3500 Not Vis. Acquired by time of RA
      - .9937 Adequate RA
        - .2014
      - .0063 Inadequate RA (.0080 RR * .79 GA ratio)
        - .5100 Vis. Acq. by 15s before CPA
          - .0007
        - .4900 No Vis. Acq. by 15s before CPA (.17/.35=.49)
          - $\boxed{.0006}$
  - .3000 All Other
    - .9937 Adequate RA
      - .2466
    - .0063 Inadequate RA (.0080 RR * .79 GA ratio)
      - $\boxed{.0016}$
- .0600 No TA
  - .9700 RA Received
    - .9937 Adequate RA
      - .0509
    - .0063 Inadequate RA (.0080 RR * .79 GA ratio)
      - $\boxed{.0003}$
  - .0300 RA Not Received
    - $\boxed{.0264}$ (Mode C * No RA, No TA is not an independent f actor)

.1000 Non Mode C (.98 Transponders * (1-.898) Non Mode C)
- .9400 TA Received
  - .7000 Bright Daylight
    - .8300 Vis. Acq. by 15s before CPA
      - .0546
    - .1700 No Vis. Acq. by 15s before CPA
      - $\boxed{.0112}$
  - .3000 All Other
    - $\boxed{.0282}$
- .0600 No TA
  - $\boxed{.0060}$

$\boxed{.0200}$ No Transponders

Failure Sum= .0943

FIGURE 27
UNRESOLVED RISK RATIO (MODE C NPRM)

Induced RR (New Logic, Mode C NPRM)

			Note
Errors	Altimetry	.0141	(.0147*.86 + .0370*.14) * .79 = .0141
	C Bits	.0020	
	Man. Int.	.0160	.00032*50=.0160
		.0321	(50 instead of 10)

Fraction of Mode C = .8800

.0282 Fraction of encounters for which incorrect RA is receivec

.9700 TA received (given RA received)

.7000 Bright Daylignt

.8300 Vis. Acq. by 15s before CPA

.0159

.1700 No Vis. Acq. by 15s before CPA

$\boxed{.0033}$

.3000 All Other

$\boxed{.0082}$

.0300 No TA received (given RA received)

$\boxed{.0008}$

Summary	.0123/.0321
Altimetry	.0054
C Bits	.0008
Man. Intruder	.0061
	.0123

Failure Sum= .0123

FIGURE 28
INDUCED RISK RATIO (MODE C NPRM)

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